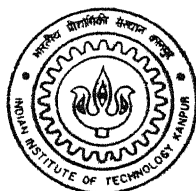


EXPERIMENTAL STUDY OF LAMINAR PREMIXED LPG-AIR FLAMES

by
AKILUR RAHMAN

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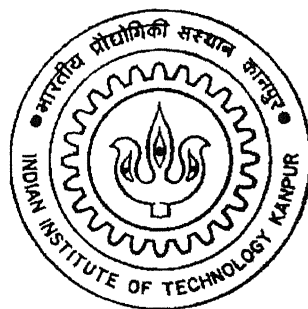


DEPARTMENT OF AEROSPACE ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR
February, 2000

EXPERIMENTAL STUDY OF LAMINAR PREMIXED LPG-AIR FLAMES

*A Thesis Submitted
in Partial Fulfillment of the Requirements
for the Degree of*
Master of Technology

by
AKILUR RAHMAN



to the
DEPARTMENT OF AEROSPACE ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR
February, 2000

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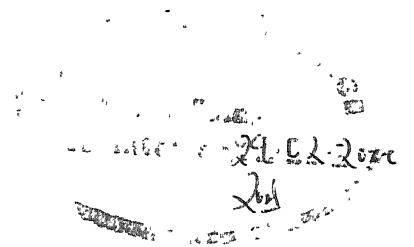
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CERTIFICATE



It is certified that the work contained in the thesis entitled **“Experimental Study of Laminar Premixed LPG-air Flames”**, by **Mr. Akilur Rahman**, has been carried out under my supervision and this work has not been submitted elsewhere for a degree.

 D. P. Mishra 24/2/2000

(Prof. D.P. Mishra)

Department of Aerospace Engineering,

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Kanpur.

February, 2000.

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Nomenclature

c_p	specific heat at constant pressure, kJ/kg-K
D	burner diameter, mm
D_c	mass diffusivity, m ² /sec
g_b	blow-off velocity gradient, 1/sec
g_f	flash-back velocity gradient, 1/sec
H	flame height, mm
Δh	heat of combustion, kJ/kg-K
k	thermal conductivity , W/m-K
\dot{m}''	mass flux, kg/s-m ²
\dot{m}'''	volumetric mass production rate, kg/s-m ³
Q	total gas flow rate, lit/min
Q_A	air flow rate, lit/min
Q_F	fuel flow rate, lit/min
R	burner radius, mm

S	flame surface area, mm ²
T_{ad}	adiabatic flame temperature, K
T_B	burned gas temperature, K
T_U	unburned gas temperature, K
u_Q	uncertainty in the gas flow rate, %
u_V	uncertainty in burning velocity, %
u_Φ	uncertainty in equivalence ratio, %
V	burning velocity, cm/sec
V_b	blow-off velocity, cm/sec
V_f	flash-back velocity, cm/sec
V_u	unburned gas velocity, cm/sec
$V_{u,n}$	normal component of V_u
$V_{u,t}$	tangential component of V_u
x	manometric deflection, mm
Y_i	mass fraction of species, i

Greek Symbol

ρ	density, kg/m ³
Φ	equivalence ratio

δ	flame thickness, mm
α	thermal diffusivity, m ² /s
v	air-fuel ratio

Subscript

ad	adiabatic
A	air
b	blow-off
B	burned gas
f	flash-back
F	fuel
i	i th species
Ox	oxidizer
p	pressure
Pr	product
U	unburned gas

Abstract

An experimental study of laminar premixed LPG (liquefied petroleum gas)-air flames is reported in this work. In order to investigate such flames, present work is divided into three sections, namely, flame structure, flame stability and flammability limits. The premixed flame is characterized by its color, shape, burning velocity, flame temperature and concentration profile. Experiments are conducted to investigate the flame structure using a cylindrical tube Bunsen like burner, over a wide range of fuel-air ratios. Burning velocity which represents the overall flame characteristics is measured by area method. The maximum burning velocity is found to be 50.4 ± 3.5 cm/sec, at an equivalence ratio of 1.1. Temperature profile is measured by Chromel/Alumel and Platinum/Platinum-13%Rhodium thermocouple at an equivalence ratio of 1.7. It is found that the peak temperature measured by Pt/Pt-13%Rh is close to the adiabatic temperature.

In order to study the stability of premixed LPG-air flames, flash-back and blow-off limits are obtained on cylindrical burners. It is observed that the maximum flash-back limit occurs at slightly rich stoichiometric composition for a 12 mm diameter burner. With further increase in burner diameter, the range of flash-back limit increases with similar overall features as that of 12 mm diameter burner. Whereas the blow-off limit increases with increase in fuel concentration. With increase in burner diameter, similar trends like flash-back are also observed for blow-off limits.

In this study, flammability limits are also measured in a standard flammability tube of 50 mm diameter and 1.2 m length, by visual observation for both upward and downward propagation of premixed flames. It is found that the flammability range for upward propagation is higher than the downward propagation. The effects of nitrogen gas on the flammability limits are also investigated for LPG-air mixture

It is noticed that the flammability range decreases with the addition of nitrogen gas for a given fuel-air mixture, keeping similar trends as reported by other investigators for hydrocarbon-air mixtures.

KEY WORDS : premixed flames, laminar LPG-air flames, burning velocity, flame temperature, flash-back limit, blow-off limit, flammability limits.

Chapter 1

INTRODUCTION

Combustion and its control are essential to our existence. In 1989, approximately 89% of the energy used in U.S.A. came from combustion sources. In daily life, we are directly or indirectly come across the electricity, which is mainly generated by burning fossil fuel. Our nation's electrical needs are met primarily by combustion. Transportation system relies entirely on combustion. In industrial processes, furnaces, boilers, refineries, glass melters, etc., are the combustion devices. Domestic burner is also a most popular combustion device. In addition, combustion is used at the other end of the product life cycle as a means of waste disposal.

Combustion can be defined as an oxidation process generating heat. The Combustion process generally occurs in a flame mode. A flame is the result of self sustaining exothermic chemical reaction, often emitting light. Flames can be broadly divided into two categories, namely, premixed and diffusion flames. In a diffusion flame, the reactants are initially separated, mixing and reaction occurs only at the interface of the flame surface itself. Diffusion flames are predominantly found in diesel engines, gas turbine combustors, etc. Contrarily, in premixed flames, fuel and oxidizer are mixed at the molecular level before letting them into the combustion zone. Premixed flames are extensively being used in domestic burners, spark ignition

engines, rocket motors, oil-fired furnaces, etc. Clean combustion demands premixed flame. It creates less pollution because of complete combustion characteristics. So, in modern days, premixed flames are preferably being used in combustion devices.

The premixed flames can be well characterized by burning velocity which represent the flame structure to a larger extent. Burning velocity is emphasized because it is the property that determines flame shape and stability characteristics. Several phenomena like ignition, quenching, blow-off, flash-back, etc. can be directly related to burning velocity.

Stability of flame is essential for designing a gas burner, power plant combustors and other important combustion devices. A flame is called stable if it lies in between flash-back and blow-off limits. Flash-back occurs when the flame enter and propagates through the burner tube or port while blow-off is the condition where flame lifts-off from the burner port and disappears. Both flash-back and blow-off are undesirable. In a gas appliances, propagation of flame through a port can ignite the relatively large volume of gas in the mixture may cause safety hazard. Blow-off phenomena is sometimes noisy.

The information of flammability limits is very important for burning a mixture and also from safety point of view. If a fuel-oxidizer mixture needs to be burnt, it must lie within the limits of flammability. A flame can propagate only within this limit. The lower fuel lean mixture is called the Lower Flammability Limit (LFL), while upper rich mixture is known as Upper Flammability Limit (UFL).

An extensive literature survey on the combustion characteristics of laminar premixed hydrocarbon-air flames has been carried out. Although, a large number of papers have reported the combustion characteristics of hydrocarbon-air flames, but there is no literature available on the studies of LPG-air flames to the best of our knowledge. LPG is the most popular domestic fuel till date. Therefore, it is decided

to analyze the LPG-air flames.

The main objective of present work is to investigate the characteristics of laminar premixed LPG-air flames by an experimental rig, which is designed and developed in our laboratory. Flame characteristics such as flame structure, flame stability and flammability limits have been reported in respective chapter of this thesis.

Chapter 2

FLAME STRUCTURE

2.1 INTRODUCTION

A premixed flame is the result of self-sustaining exothermic chemical reaction within a certain range of fuel-oxidizer mixture ratio. A schematic of one dimensional flame is shown in fig.2.1. The flame can be divided broadly into two zones, namely preheat and reaction zones as shown in fig.2.2. In preheat zone, no significant chemical reaction takes place. The temperature of the unburnt gas is raised mainly by heat conduction. This zone acts as a heat sink. Because of the increase in temperature, the unburnt gas expands and is accelerated. The temperature profile is concave upward. While, in reaction zone, chemical reaction takes place with subsequent liberation of heat. The temperature profile is concave downward. The point where the two curves meet is called the point of ignition. The temperature corresponding to this point is called ignition temperature. It is defined as the temperature in a flame below which the reaction rate is negligible. Ignition temperature has practical application in fire safety.

Flame structure consist essentially of two parts. The first part involves the analysis of factors which determine the shape of the combustion wave. For this

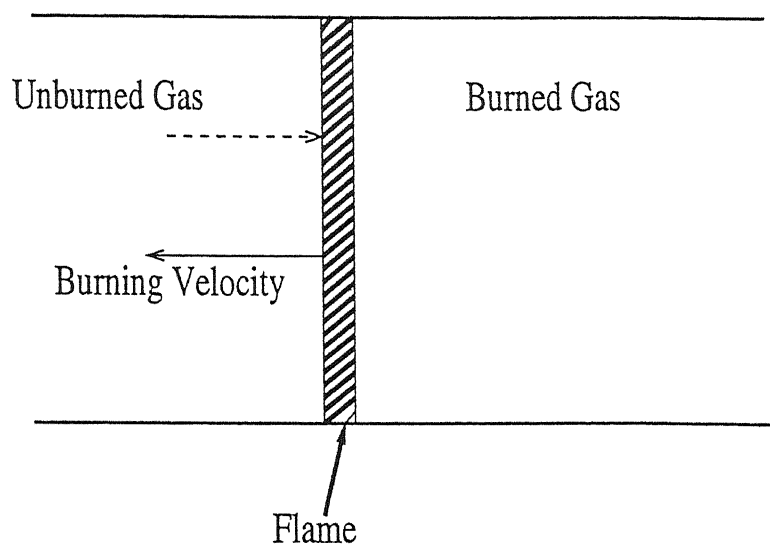


Figure 2.1: One dimensional flame

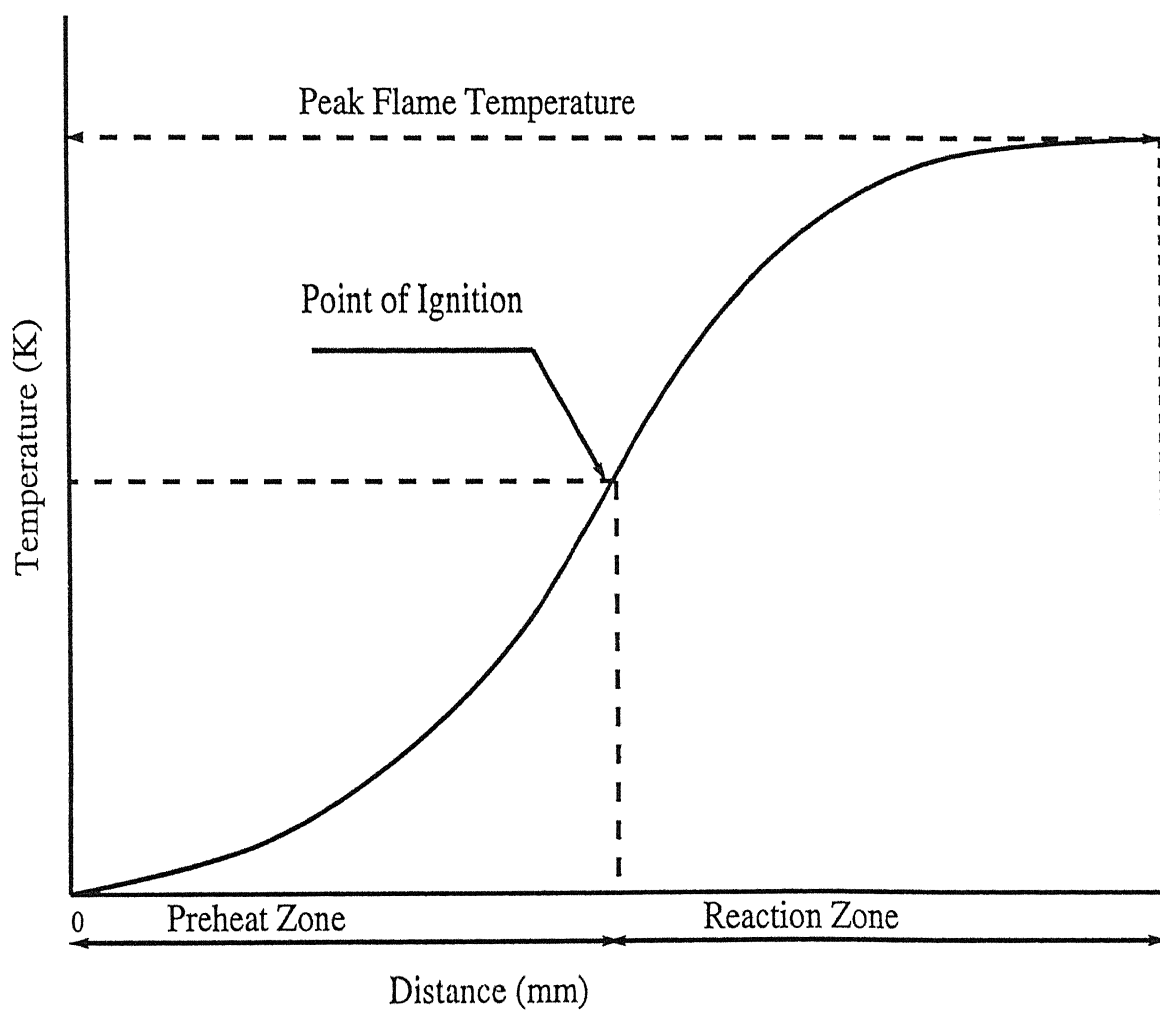


Figure 2.2: Temperature profile of a flame front

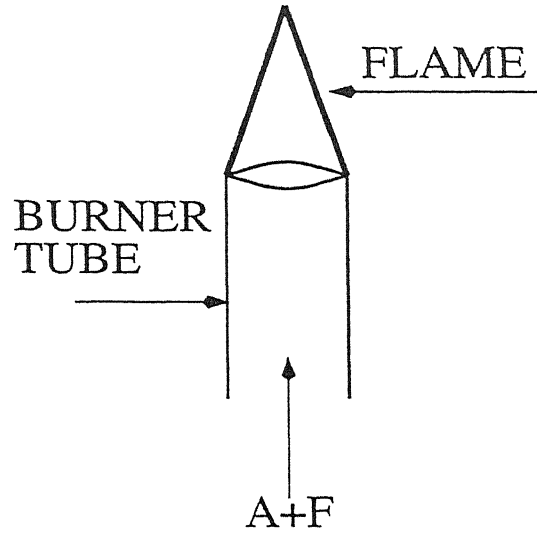


Figure 2.3: Bunsen flame schematic

part, burning velocity is the most important parameter, since several phenomena like quenching, blow-off, flash-back, etc., can be related to the burning velocity. Burning velocity is defined as the velocity of flame normal to the flame front with respect to fresh reaction mixture. A schematic of Bunsen flame is shown in fig.2.3. For the flame to remain stationary, the burning velocity must equal the velocity of the normal component of the unburnt gas at each location, as illustrated in the vector diagram in fig.2.4. The second part involves the descriptions of the temperature and concentration profile across the combustion wave. The understanding of flame propagation is essential for design and development of combustion devices.

2.2 LITERATURE SURVEY

A literature survey on the structure of laminar premixed LPG-air flames has been conducted for the present work. It is found out that several configuration like Bunsen burner, Powling burner, constant volume bomb, flammability tube, etc., have been used till date to investigate the flames. The burning velocity being the important characteristics of the premixed flames, it has attracted several researchers

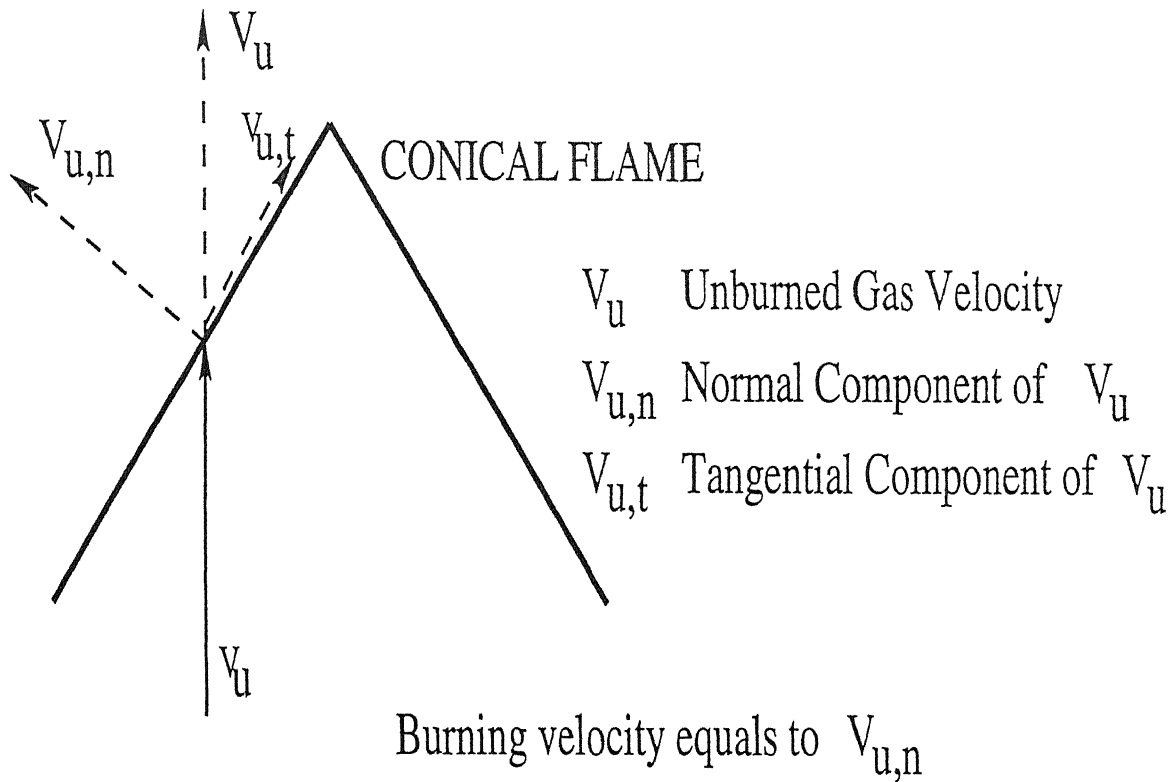


Figure 2.4: Velocity vector diagram of flame front

to investigate in detail, both for stationary and non-stationary flames. For characterizing the burning velocity of stationary flames, different type of burners, namely, Bunsen burner, Powling burner, etc., have been used.

Bunsen Burner

This burner was invented by Bunsen (1855), from which he got premixed stabilized flames. He observed a conical flame, similar to shown in fig. 2.3. Later on, conical flames have been used by the majority of workers. The gas velocity normal to the flame front has been measured either directly or indirectly. The burning velocity was assumed constant over the entire surface, which can be estimated by several methods, such as area method, angle method, etc.

The measurement of burning velocity by area method was proposed by Guoy [1].

He used a cylindrical Bunsen burner for this experiment. In this method, burning velocity was obtained by volume flow rate of the gas divided with the flame surface area. He approximated the flame to a right circular cone with base equal to the burner diameter. The flame area could easily be found from measurement of flame height. Subsequently, Culshaw & Garside [2] measured the flame area by graphical integration method. In an attempt to avoid the complication introduced at the tip and base of the flame, truncated cone method was proposed by Dery [3]. In truncated cone method, the disturbed region of the tip and base of the flame are eliminated. The resulting burning velocity corresponds to the central frustum flame region.

Another method reported in the literature is known as angle method. This method was proposed by Guoy [1]. In this method, burning velocity is obtained from the measurement of gas velocity and apex angle of the cone, as shown in the fig.2.4. When this method was proposed, the results were found to depend on the part of luminous cone measured. Subsequently, Broez [4] noticed the differences in cone angle between luminous, shadow and schlieren surfaces. Later on, Smith & Pickering [5] measured the cone angle at a radius of 0.707 of the burner tube radius by assuming the parabolic distribution of gas velocity. Other observation was also made by Garner et al. [6], who suggested that the best results could be obtained at a radius of 0.4 of the burner tube radius. However, it was concluded that the formation of straight cone is difficult to achieve in a cylindrical burner tube.

The use of nozzle in a Bunsen burner is reported in the literature. It enables the creation of a uniform velocity profile for the unburnt gas and the formation of straight sided flame cone. Mache & Hebra [7] introduced the nozzle burner for the first time to obtain nearly straight sided flames. After a detailed examination of above method, Caldwell [8] showed that the uniform velocity across the nozzle

tended to revert to a parabolic velocity distribution in a comparatively short distance beyond an exit plane. Subsequently, Garner et al. [9] investigated the variation of velocity across the exit plane and concluded that there is always a boundary layer of appreciable thickness and this accounts for the inability to obtain a straight sided flame cone. Although angle measurement method is particularly suited to the nozzle burner, Fells & Rutherford [10] observed a possible error of $\pm 30\%$ from the use of angle method. They also determined the burning velocity of methane-air flames by area method. However, it was found that the stabilization of flame on a nozzle is bit difficult over a wide range of fuel-air ratios.

Flat Flame Burner

In a flat flame burner, a one dimensional disk like stationary flame can be obtained at a short distance above the burner matrix. The method of measuring the burning velocity was reported by Egerton & Thabet [11]. In this method, burning velocity is obtained by volume flow rate of gas divided with the flame surface area. The disadvantage of this method is that it is difficult to define the edges of flame for measuring its area accurately.

In non-stationary flames, the flame moves through the initially quiescent mixture. Several methods have been used by researchers to determine the burning velocity of non-stationary flames.

Tube Method

This is one of the earliest method and was proposed by Mallard & Le Chatelier [12]. They ignited the mixture at the open end of the tube and photographed the flame front propagation towards the closed end. Subsequently, Guenoche & Guoy [13] concluded that by using this method, accurate determination of the flame surface

area is difficult due to non-symmetric nature of the flame. In later studies, Fuller et al. [14] developed a flammability tube and determined the burning velocity from multiple exposure photographs of the flame moving down the tube. Subsequently, Shrikant et al. [15] measured the burning velocity of wood gas-air flames by passing it through the tube and observing by a video camera. Burning velocity measured by this method is expected to be higher due to convective rise of the burnt gases, which increases the burning velocity.

Constant Volume Bomb Method

In this method, a containing envelope surrounds the explosive mixture. The mixture is ignited centrally and the rate of propagation of the spherical flame is measured. Close to the point of ignition, the high curvature of the flame causes a reduction in the burning velocity [16], but if a large vessel is used, more than 25 cm diameter then remote from the spark, the flame front is approximated as one dimensional. This method is generally considered as a versatile and accurate method for a wide range of fuel-air mixtures [17,18]. However, the experimental set up required for this method needs very sophisticated instrumentation.

Temperature Measurement

The temperature measurement is an important parameter for characterizing the structure of premixed flames. In literature, different methods are available, among which, temperature measured by thermocouple is the most conventional method.

The first reported literature on the temperature measurement of hydrocarbon flames by the thermocouple is the work of Friedman [19], who measured the temperature profile of propane-air flames on a flat flame burner using Platinum/Platinum-13%Rhodium thermocouple. He developed a thermocouple traversing technique to

minimize the perturbation in the flame by the thermocouple. Subsequently, Cook & Simmons [20] reported the temperature profile of propane-oxygen-argon flames by using Pt/Pt-Rh thermocouple. Temperature measurement using Pt/Pt-13%Rh thermocouple for propane-air flames on a flat flame burner was reported by Kaiser et al. [21].

In later studies, Shrikant et al. [15] reported the temperature profile of wood gas-air flames at ambient condition by using Chromel/Alumel and Platinum/Platinum-13%Rhodium thermocouple. In this measurement, Chromel/Alumel recorded lower flame temperature than the Pt/Pt-13%Rh and the difference was of the order of 150-250 K.

The thermocouple disturbs the flow to some extent. However, other new techniques have forwarded which offer the possibility of measurement without any disturbance to the flow [22].

2.3 EXPERIMENTAL PROCEDURE

In order to investigate the structure of laminar premixed LPG-air flames, an experimental set up has been designed and developed in our laboratory. A schematic of this experimental set up is shown in fig.2.5. The LPG required for this experimental work is taken from commercially available LPG cylinder. The air needed for combustion of LPG is supplied from air compressor, as shown in fig.2.5. The flow rate of LPG and air are controlled properly by means of fine needle valves. The amount of LPG is metered while passing through a calibrated capillary flow meter. The Capillary flow meter has been calibrated by soap bubble method as described in detail in section 2.4. Air is allowed to pass through a calibrated rotameter to measure the flow rate.

The LPG and air are mixed thoroughly in a mixing chamber as shown in fig.2.5,

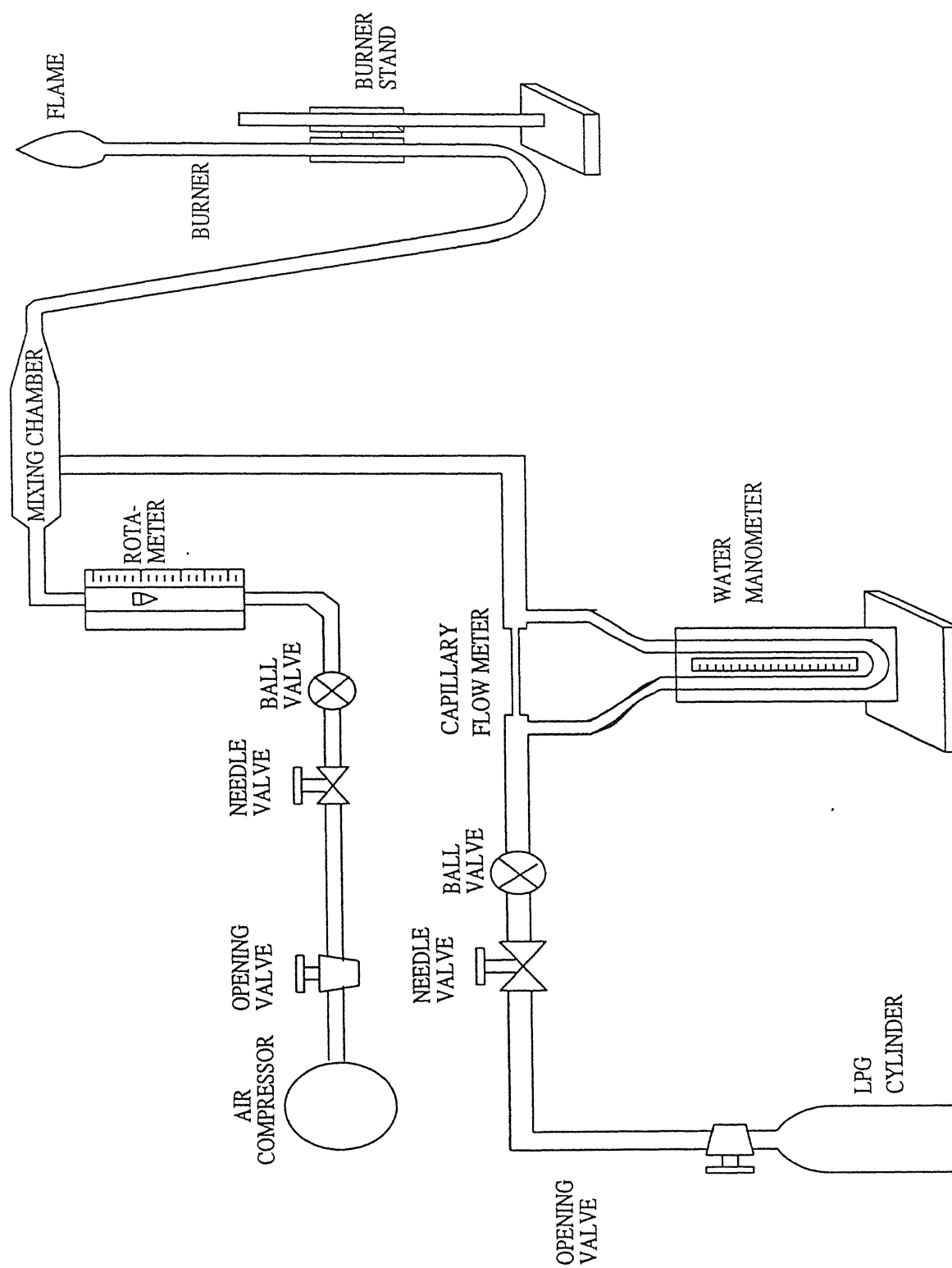


Figure 2.5: Schematic of experimental set up

where the desired level of LPG and air ratio is achieved. The gases are passed to a burner (cylindrical tube), which has sufficient length to ensure a fully developed laminar flow. Then, flame is obtained by igniting the mixture at the tip of the burner. All care is taken to ensure that the whole system is leak proof.

2.4 MEASUREMENT METHODS

In the present experimental work, following measurements are made to study the laminar premixed LPG-air flames.

- Gas Flow Measurement
- Burning Velocity Measurement
- Temperature Profile Measurement

The composition of LPG is analyzed by a gas chromatograph. According to our analysis, LPG contains 70% butane (both iso and normal) and 30% propane.

2.4.1 Gas Flow Measurement

In the present work, measurements of gas flow rate is essential to maintain the desired air-fuel ratio. Air flow rate is measured by a calibrated rotameter using wet gas flow meter as a primary flow meter. The calibration error is found to be $\pm 3\%$. LPG flow rate is measured by a capillary flow meter, which is being calibrated by soap bubble flow meter.

Calibration of capillary flow meter

A schematic of experimental set up which is used to calibrate the capillary flow meter is shown in fig.2.6. LPG is allowed to pass through the capillary flow meter

and subsequently passes through the soap bubble flow meter as shown in fig.2.6. The soap bubble flow meter consist of glass tube with internal diameter of 2.48 cm & 100 cm long and a rubber bulb containing soap solution. A water manometer is connected across the capillary flow meter, which provides the pressure drop of gas flow. When rubber bulb is pressed, a thin soap film is formed whose front is moved upward by the flowing fluid. The time taken by the the soap film front to cover a distance of 70 cm is measured and film velocity is calculated. The film is so light that its effect on gas velocity will be insignificant. Therefore, velocity of gas is assumed to be the film velocity. The gas velocity is proportional to the flow rate. Similar runs have been carried out for a wide range of flow rates of LPG and the corresponding pressure drop across the capillary flow meter is measured, which are plotted as shown in fig.2.7. A best fit curve is drawn by taking all the data points, whose equation is given as $0.25x+0.16$, where x is the manometric deflection. This equation is used to calculate the flow rate of LPG.

2.4.2 Burning Velocity Measurement

Burning Velocity is an important parameter in the study of laminar premixed LPG-air flames. Therefore, extensive studies have been reported in literature to determine the burning velocity. During earlier studies, burning velocity in a Bunsen burner was measured by area or angle method. Later on, different new methods were forwarded with sophisticated instrumentation.

The present investigation is based on the area method. In this method, direct photograph of stabilized flames over a wide range of fuel-air ratios are taken as shown in fig.2.8. Photographs show that the flame front is conical and slightly rounded at the tip. For the sake of simplicity, to calculate its surface area, shape of the flame is assumed to be a perfect cone. The error due to rounding of the tip is not very large,

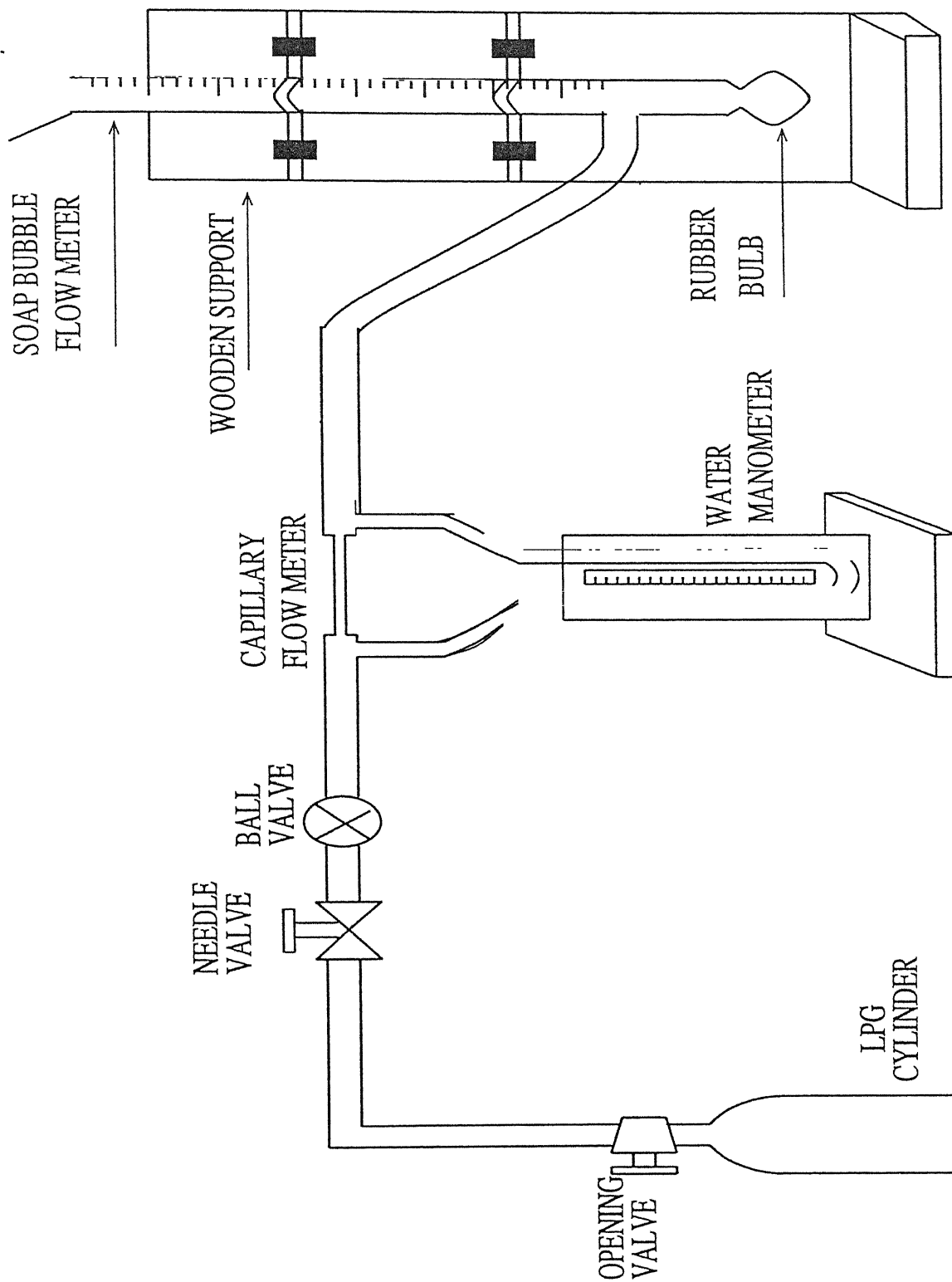


Figure 2.6: Schematic of test rig used to calibrate capillary flow meter

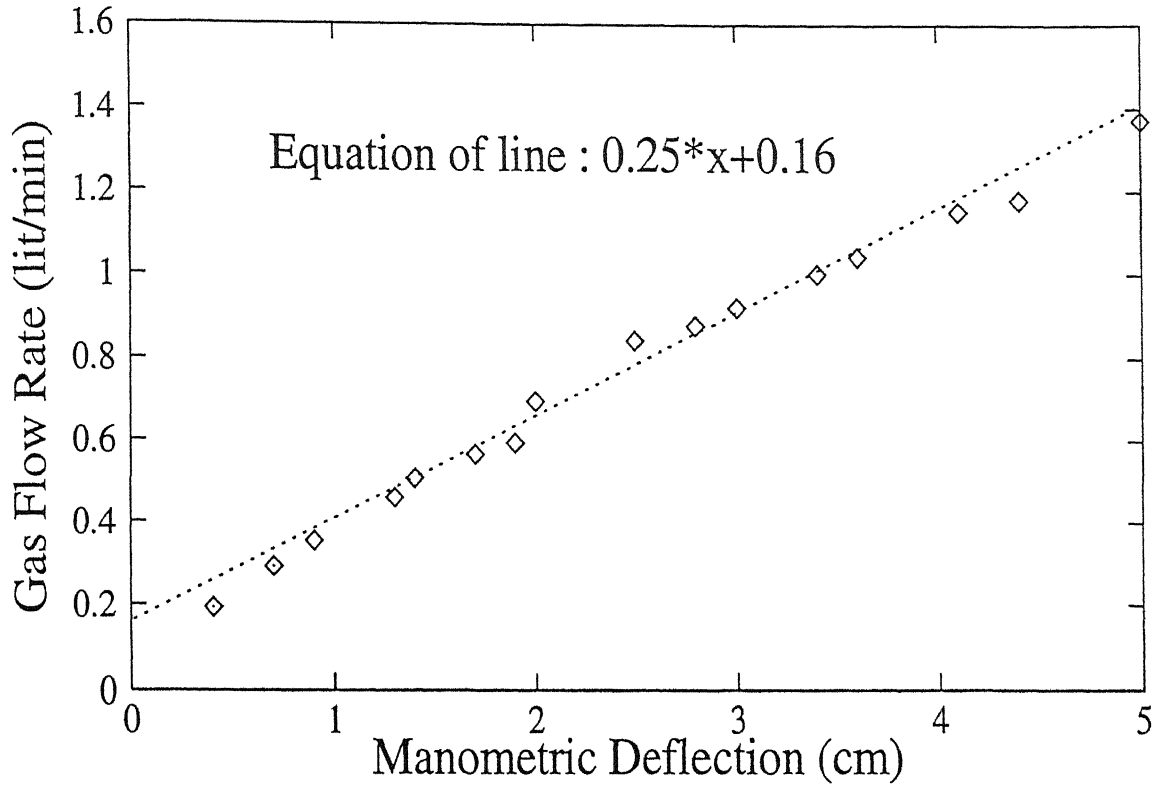


Figure 2.7: Calibration curve of capillary flow meter

because of the relative small contribution of this region to the total surface area.

By the above mentioned area method, burning velocities have been calculated for different equivalence ratios. The equivalence ratio is denoted by Φ , and is defined as :

$$\Phi = \frac{(Fuel/Air)_{actual}}{(Fuel/Air)_{stoichiometry}}$$

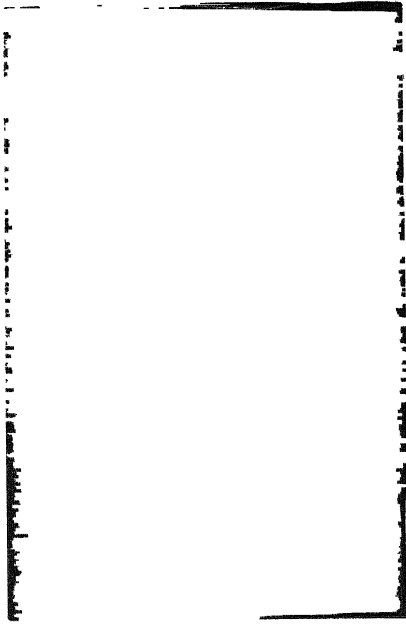
Sample calculation

At stoichiometric composition ($\Phi = 1$)

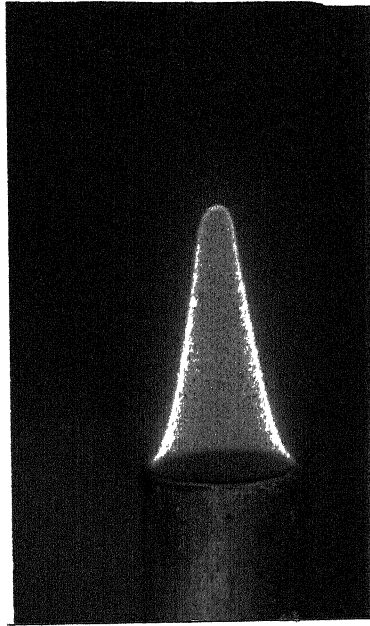
Air flow rate (Q_A) = 26.2 lit/min

Fuel flow rate (Q_F) = $0.25x + 0.16$, where x is the manometric deflection in cm.

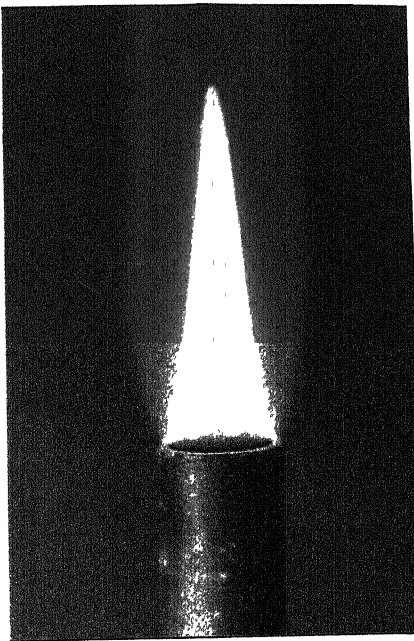
$x = 30$ mm



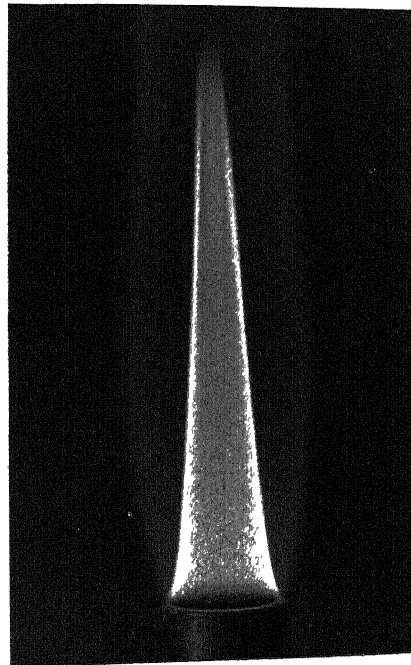
Equivalence ratio 0.8



Equivalence ratio 1.19



Equivalence ratio 1.35



Equivalence ratio 1.5 (Tip Opening)

Figure 2.8: Flame configuration for LPG-air flames

$$Q_F = 0.25 \times 3 + 0.16 = 0.91 \text{ lit/min}$$

$$\text{Flame height } (H) = 32 \text{ mm}$$

$$\text{Burner radius } (R) = 9 \text{ mm}$$

$$\text{Flame surface area } (S) = \pi \times 9 \times \sqrt{32^2 + 9^2} = 939.88 \times 10^{-6} \text{ m}^2$$

$$\text{Total Volume flow rate } (Q) = 26.2 + 0.91 = 27.11 \text{ lit/min} = 0.452 \times 10^{-3} \text{ m}^3/\text{sec}$$

$$\text{Burning Velocity } (V) = Q/S = 0.452 \times 10^{-3} / 939.88 \times 10^{-6} = 48.09 \text{ cm/sec}$$

2.4.3 Temperature Profile Measurement

Flames are always associated with the high temperature. Several parameter regarding the flame structure are related to the flame temperature. Therefore, a sound knowledge of temperature profile is important. In the present experimental work, temperature profile is measured by immersing a thermocouple in the flame. The technique utilizes the thermoelectric properties of the conductors. When two dissimilar conductors, which are maintained at different temperatures and connected at a junction, a thermoelectric potential is developed, which is proportional to the difference in temperature.

In order to investigate the temperature profile, temperature measuring probe has been designed and developed, as shown in fig.2.9. The thermocouple is fixed between two arms of U-shaped support. The distance between the two arms is 13 cm, which is sufficient to save the support from the influence of flame and also the aerodynamics of flame would not be effected by the presence of the probe. The measuring probe is connected to a traverse with the help of an iron rod, which gives proper movement to the thermocouple. Thermocouple is made by spot welding and effort is made to have a small spherical bead. Thermocouple bead is connected to a micro-Voltmeter, which monitors voltage. This voltage can be converted to temperature difference of thermocouple junction and ambient with the help of standard available charts. The

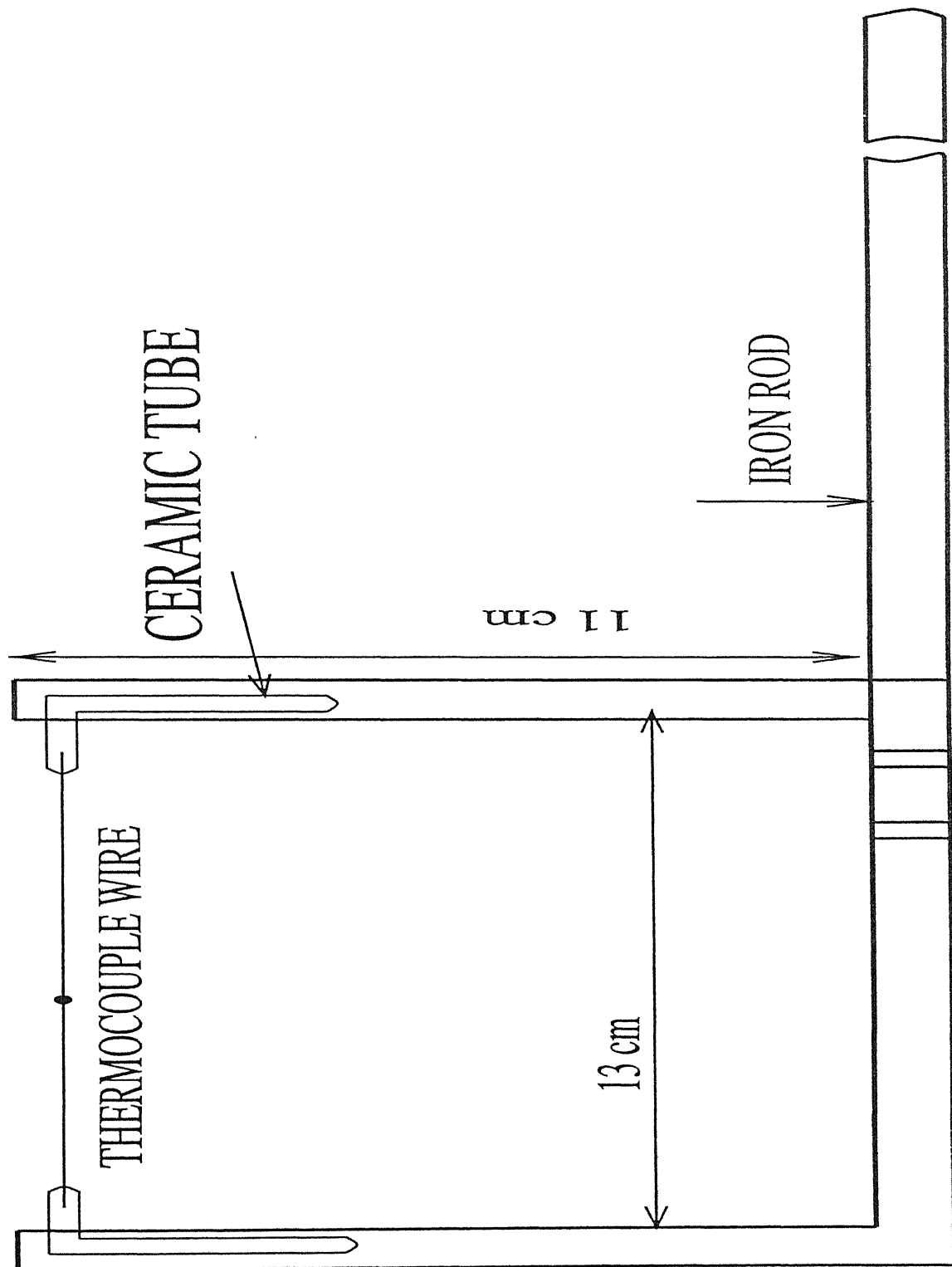


Figure 2.9: Temperature measuring probe

ambient temperature is measured by a mercury thermometer.

2.5 RESULTS AND DISCUSSION

Experiments are conducted to study the structure of laminar premixed LPG-air flames covering a wide range of fuel-air ratios. We have started with a lean LPG-air mixture of equivalence ratio of 0.75 and gradually increased the LPG concentration.

The following changes were observed in the flame as shown in fig.2.8 :

1. The flame is blue and luminous surface is continuous for equivalence ratio up to 0.8. This blue radiation results from excited CH radicals in the reaction zone [23].
2. The color of the flame changes to green for equivalence ratio up to 1.25. This is due to the radiation from excited C_2 [23].
3. At equivalence ratio of 1.35, the entire flame changes to green.
4. At the equivalence ratio of 1.5, luminous surface is not continuous. In other words, we find tip opening of the flame as shown in fig.2.8.

For lean mixture ($\Phi=0.75$), it is found out that the structure of the flame front is conical and slightly rounded at the tip. When the concentration of LPG is increased, rounding tendency at the tip of the flame also increases and finally tip opening occurs. Tip opening is an interesting phenomena in the study of premixed flames.

Present investigation shows that the tip opening of laminar premixed LPG-air flame occurs at rich stoichiometric composition at equivalence ratio of 1.5 (4.95% of LPG), as shown in fig.2.8. Similar tip opening phenomena was also observed for propane-air & butane-air flames as reported in the work of Law et al. [24]. By detailed examination of this work, it is found that tip opening occurs at 4.4%

concentration of butane in butane-air flames and 5.7% concentration of propane in propane-air flames. However, in case of LPG gas (containing 70% butane & 30% propane), tip opening is found to appear between butane-air & propane-air flames. Thus, the present result of appearance of tip opening is incommensurable with the reported data of Law et al. [24].

The phenomena of tip opening can be explained quantitatively. For rich LPG-air flames, more fuel is likely to occur at the tip region because air being more mobile than LPG defocused to a greater extent. This may lead to the flame extinction at the tip first, resulting in tip opening. However, tip opening is not observed for lean fuel mixtures.

Experiments are conducted to determine the burning velocities over a wide range of fuel-air ratios by area method, as mentioned in section 2.4. Results of burning velocity over various equivalence ratios are presented in fig.2.10. It is evident from the figure that below the stoichiometric composition, burning velocity increases with increase in fuel concentration. It attains a maximum value at slightly rich stoichiometric composition of equivalence ratio 1.1. With further increase in fuel concentration, burning velocity decreases. This is a general tendency of hydrocarbon flames that the maximum burning velocity occurs at slightly rich stoichiometric composition, as reported in open literature.

In order to validate our present results of the burning velocity, comparisons are made with the burning velocities of LPG-air flames, measured by Sharma et al. [25], as shown in fig.2.11. It can be observed from the figure that the measured values of Sharma et al. [25] are quite different from that of our present results. On detailed examination, it is observed that the reported results were obtained by using LPG, which contains 95% butane and other hydrocarbons (details not given), whereas our results are obtained by using LPG, containing 70% butane and 30% propane,

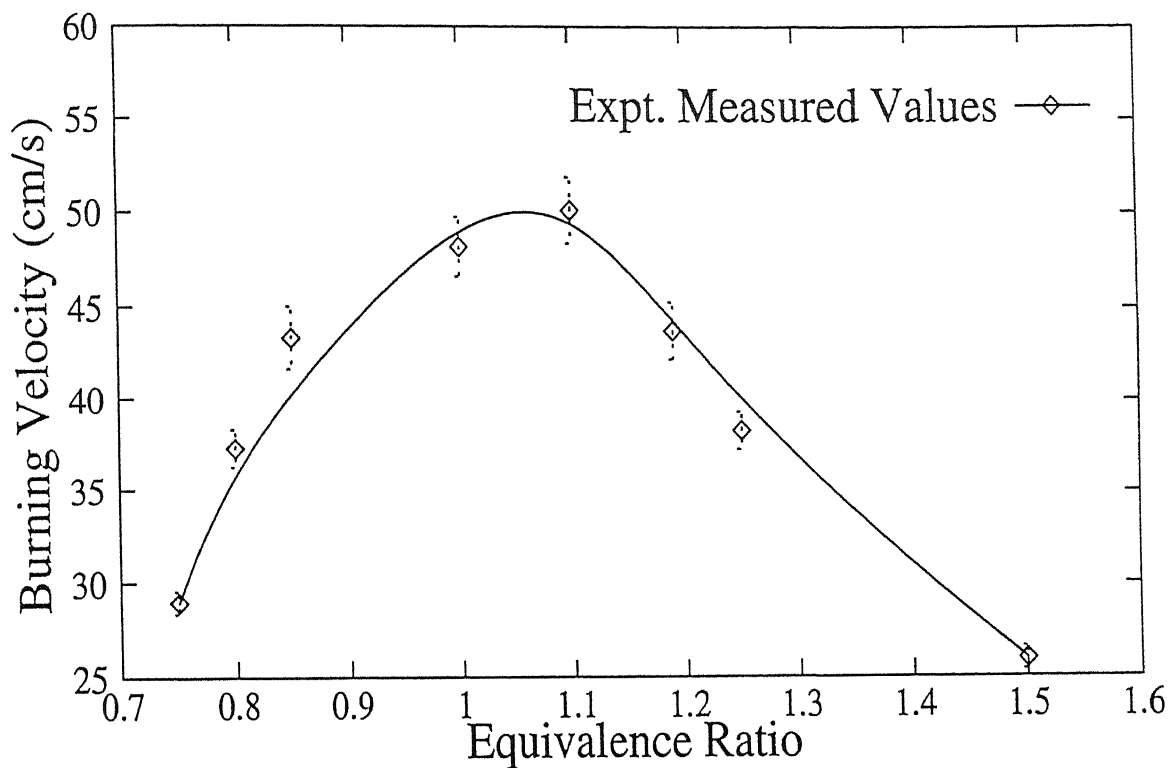


Figure 2.10: Experimental results of burning velocity

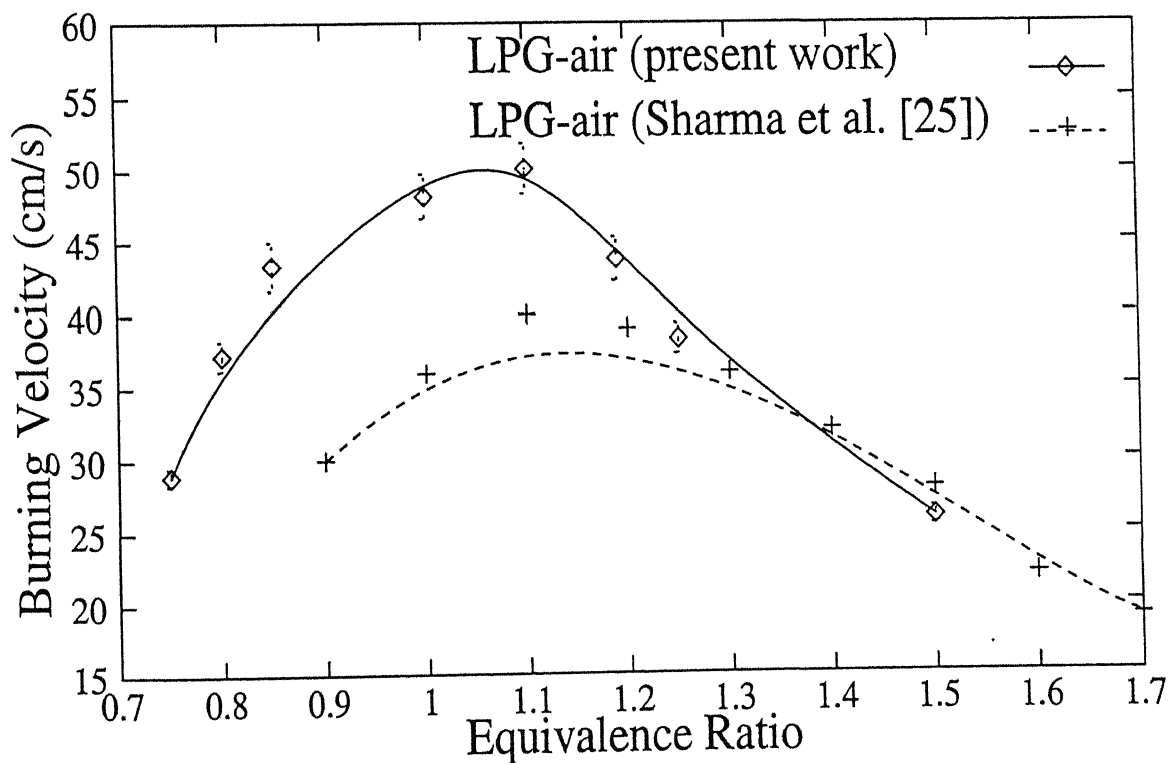


Figure 2.11: Comparison of burning velocities of LPG-air flames

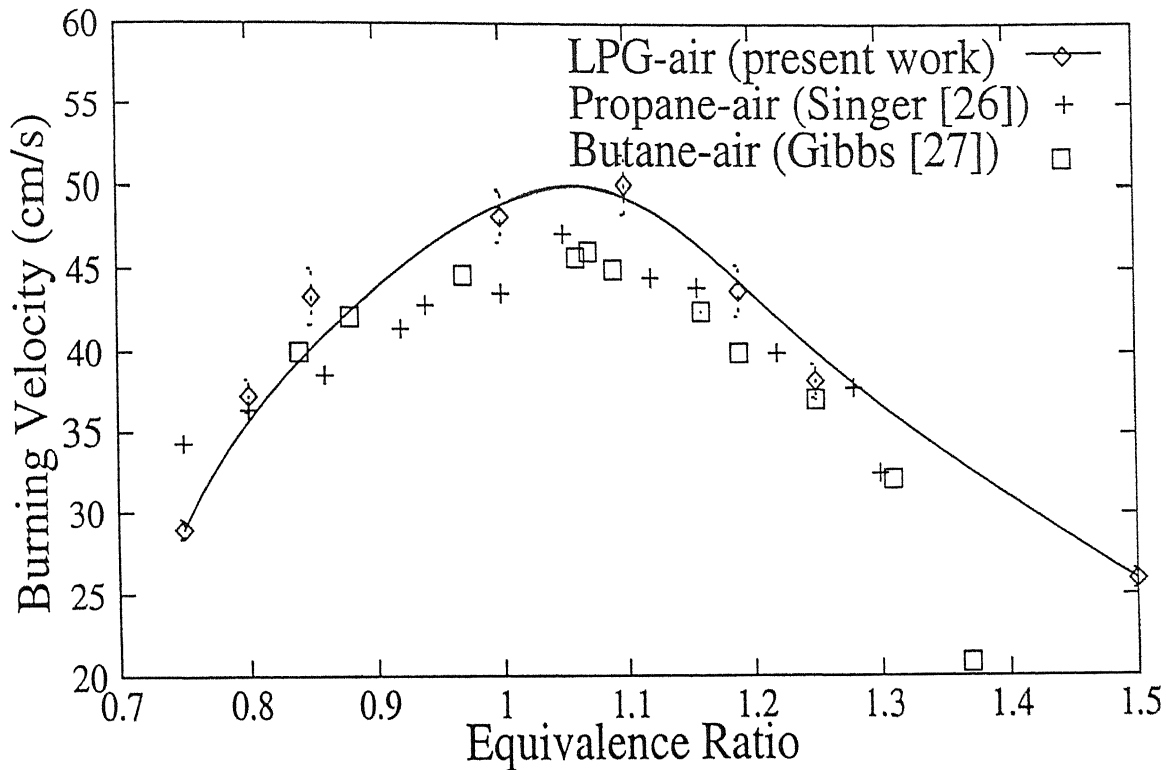


Figure 2.12: Burning velocities of different hydrocarbon flames

measured by a gas chromatograph.

As no reliable data of burning velocity of LPG-air flames are available in the literature, therefore, efforts are being made to compare the present results with the reported data of propane-air and butane-air flames. Comparisons of the present results are made with the results of Singer [26] and Gibbs et al. [27], as shown in fig.2.12. It can be concluded that the present results are within the expected trend of propane-air and butane-air flames.

Theoretical Analysis

A theoretical analysis for calculating the laminar burning velocity [28] has been made by applying mass, species and energy conservation equations on the basis of following assumptions :

1. One dimensional, steady flow.
2. Kinetic and potential energies, viscous shear work and thermal radiation are all neglected.
3. The velocity gradient are so small that viscous inertial term in the momentum equation is very small. Hence, the momentum equation reduces to pressure being constant through the flame.
4. The diffusion of heat and mass are governed by Fourier and Fick's law, respectively.
5. Lewis number (Le), which expresses the ratio of thermal diffusivity to mass diffusivity, i.e.,

$$Le = \frac{\alpha}{D_c} = \frac{k}{\rho c_p D_c} \quad (2.1)$$

is unity.

6. Specific heat of given mixture is constant.
7. Combustion product is formed in a single step exothermic reaction.

In order to understand the flame propagation, we are applying conservation of mass, species and energy equation to the differential control volume as shown in fig.2.13.

Mass conservation equation :

$$\frac{d(\rho V_x)}{dx} = 0 \quad (2.2)$$

or

$$\dot{m}'' = \rho V_x = \text{constant} \quad (2.3)$$

where,

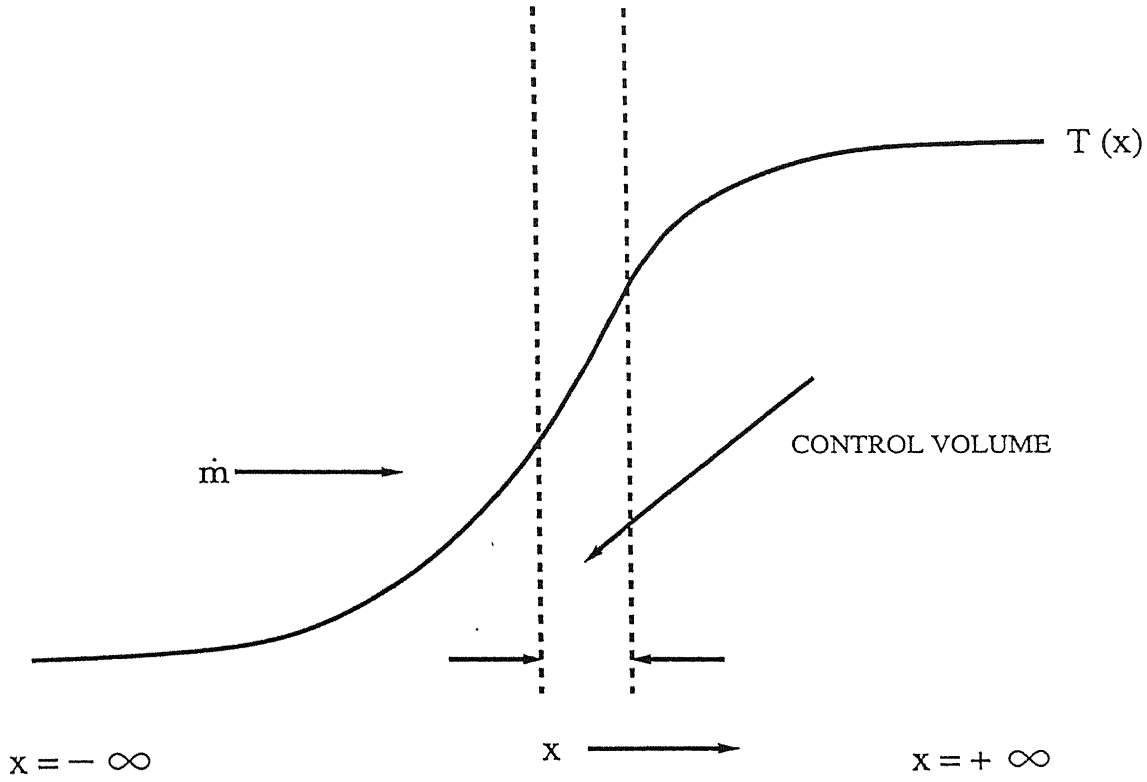


Figure 2.13: Control volume for flame analysis

\dot{m}'' = mass production rate per unit area

ρ = gas density

V = burning velocity.

Species conservation equation :

$$\frac{d\dot{m}_i''}{dx} = \dot{m}_i''' \quad (2.4)$$

or, with the application of Fick's law :

$$\frac{d}{dx} \left[\dot{m}'' Y_i - \rho D_c \frac{dY_i}{dx} \right] = \dot{m}_i''' \quad (2.5)$$

where,

\dot{m}_i'' = mass production rate of species i per unit area

y_i = mass fraction of species i

D_c = mass diffusivity

\dot{m}_i''' = mass production rate per unit volume.

The production rate of fuel \dot{m}_F''' and oxidizer \dot{m}_{O_x}''' are negative, since these species are being consumed.

For a simple reaction :-

1 kg fuel + v kg of oxidizer \rightarrow $(v + 1)$ kg product

Thus,

$$\dot{m}_F''' = (1/v)\dot{m}_{O_x}''' = -(1/v + 1)\dot{m}_{Pr}''' \quad (2.6)$$

Equation (2.6) becomes for each species :-

Fuel

$$\dot{m}'' \frac{dY_F}{dx} - \frac{d(\rho D_c \frac{dY_F}{dx})}{dx} = \dot{m}_F''' \quad (2.7)$$

Oxidizer

$$\dot{m}'' \frac{dY_{O_x}}{dx} - \frac{d(\rho D_c \frac{dY_{O_x}}{dx})}{dx} = v\dot{m}_F''' \quad (2.8)$$

Products

$$\dot{m}'' \frac{dY_{Pr}}{dx} - \frac{d(\rho D_c \frac{dY_{Pr}}{dx})}{dx} = -(v + 1)\dot{m}_F''' \quad (2.9)$$

Energy conservation equation:

$$\dot{m}'' \frac{dT}{dx} - \frac{1}{c_p} \frac{d(k \frac{dT}{dx})}{dx} = \frac{-\dot{m}_F''' \Delta h}{c_p} \quad (2.10)$$

where,

\dot{m}'' = mass production rate per unit area, $\frac{dT}{dx}$ = temperature gradient, c_p = specific

heat at constant pressure, k = thermal conductivity of gas, Δh = heat of combustion of fuel.

Our objective is to find an useful expression for laminar burning velocity, which is related simply to mass flux, \dot{m}'' ,

$$\dot{m}'' = \rho V \quad (2.11)$$

Equation (2.10) can be solved by satisfying the following boundary conditions :
for upstream of the flame,

$$T(x \rightarrow -\infty) = T_U \quad (2.12)$$

$$\frac{dT}{dx}(x \rightarrow -\infty) = 0 \quad (2.13)$$

and for downstream of the flame,

$$T(x \rightarrow +\infty) = T_B \quad (2.14)$$

$$\frac{dT}{dx}(x \rightarrow +\infty) = 0 \quad (2.15)$$

For simplicity, we assume a linear temperature profile that goes from T_U (Unburned gas temperature) to T_B (burned gas temperature) over the small distance δ as shown in fig.2.14. δ is defined as the flame thickness.

Integrating equation (2.10) with respect to x and applying the condition at $-\infty$ and $+\infty$, yields :

$$\dot{m}'' [T]_{T_U}^{T_B} - \frac{1}{c_p} k \left[\frac{dT}{dx} \right]_0^0 = \frac{-\Delta h}{c_p} \int_{-\infty}^{+\infty} \dot{m}_F''' dx \quad (2.16)$$

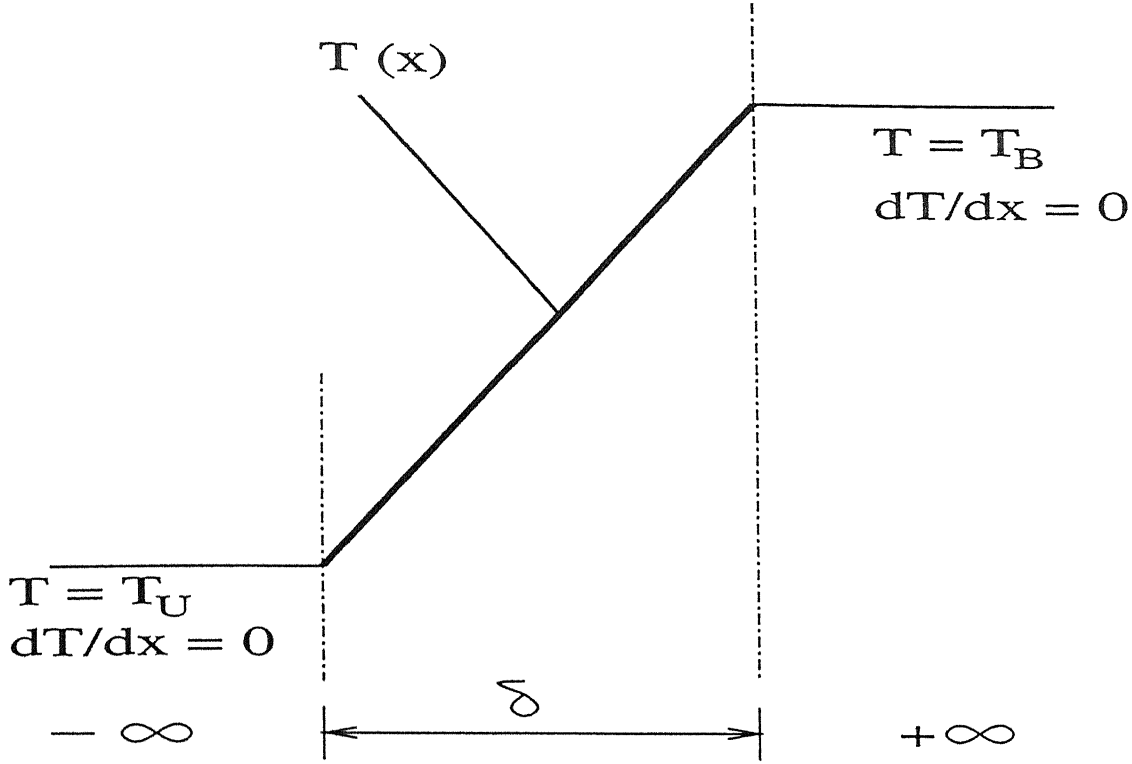


Figure 2.14: Assumed temperature profile for flame analysis

which by evaluating the limits, simplifies to

$$\dot{m}''(T_B - T_U) = \frac{-\Delta h}{c_p} \int_{-\infty}^{+\infty} \dot{m}_F''' dx \quad (2.17)$$

We can change the limits on the reaction rate integral appearing on the right side of equation (2.17) from space to temperature, since \dot{m}_F''' is only non-zero between T_U and T_B over the region δ , i.e.,

$$dx = \frac{\delta}{T_B - T_U} dT \quad (2.18)$$

With the change of variables,

$$\dot{m}''(T_B - T_U) = \frac{-\Delta h}{c_p} \cdot \frac{\delta}{(T_B - T_U)} \int_{T_U}^{T_B} \dot{m}_F''' dT \quad (2.19)$$

and recognizing the definition of average reaction rate,

$$\bar{\dot{m}}_F''' = \frac{1}{(T_B - T_U)} \int_{T_U}^{T_B} \dot{m}_F''' dT \quad (2.20)$$

we obtain a simple result, that

$$\dot{m}''(T_B - T_U) = \frac{-\Delta h}{c_p} \delta \bar{\dot{m}}_F''' \quad (2.21)$$

The above equation (2.21) is a simple algebraic equation involving the two unknowns \dot{m}'' and δ ; thus, we need to find another equation to complete the solution. This can be done by following the same procedure as before, but now integrating from $x = -\infty$ to $x = \delta/2$. Since the reaction zone of flame lies in the high temperature region, it is reasonable to assume that \dot{m}_F''' is zero in the interval $-\infty < x \leq \delta/2$. Noting that at $x = \delta/2$,

$$T = \frac{T_B + T_U}{2} \quad (2.22)$$

and

$$\frac{dT}{dx} = \frac{T_B - T_U}{\delta} \quad (2.23)$$

With this modified limit, equation (2.10) becomes,

$$\dot{m}'' \frac{\delta}{2} - \frac{k}{c_p} = 0 \quad (2.24)$$

Solving equation (2.21) and (2.23) simultaneously, yields

$$\dot{m}'' = \left[2 \frac{k}{c_p^2} \frac{(-\Delta h)}{(T_B - T_U)} \bar{\dot{m}}_F''' \right]^{1/2} \quad (2.25)$$

Applying the definition of burning velocity, $V = \dot{m}''/\rho$, and the thermal diffusivity,

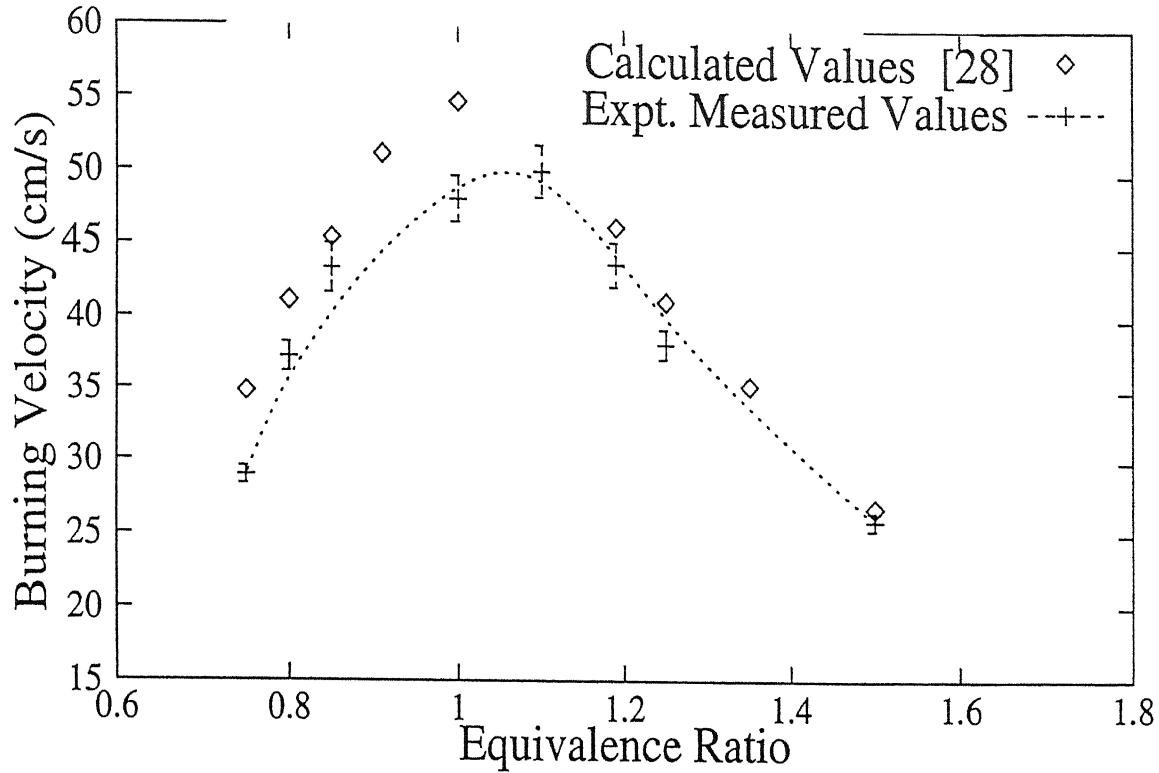


Figure 2.15: Comparison of burning velocities (experimental & calculated)

$\alpha = k/\rho c_p$, and recognizing that $\Delta h = (v + 1)c_p(T_B - T_U)$, we obtain an equation to get the burning velocity :

$$V = [-2\alpha(v + 1)\frac{\bar{m}_F'''}{\rho}]^{1/2} \quad (2.26)$$

This equation can be used to calculate the burning velocity (V) for different air-fuel ratios. Values of the burning velocity by theoretical analysis are plotted with the measured values in a single plot as shown in fig.2.15. It can be noticed from the figure that the burning velocities calculated by theoretical analysis are higher than the experimentally measured values. However, both values follow the same trend. Theoretical results are based on adiabatic flame temperature, but in actual situation, it is not possible due to heat losses. Actual temperature is lower than adiabatic, resulting in lower burning velocity.

Temperature Profile of the Flame

In the present work, experiments are also conducted to measure the flame temperature, which is an important parameter in the study of flame structure. Initially, Chromel/Alumel thermocouple of wire diameter 0.5 mm (bead diameter-0.8 mm) is used to measure the temperature profile of laminar premixed LPG-air flame. Since the melting point of Chromel/Alumel is 1650K, which is substantially lower than the adiabatic flame temperature of stoichiometric LPG-air mixture ($T_{ad} = 2276K$). Therefore, it is decided to investigate the temperature profile across the flame around limit mixtures such that the Chromel/Alumel can withstand the flame temperature.

On examination of the lean mixtures, it was not easy to stabilize a flame near a lean fuel-air mixtures, although flame temperature is lower than the melting temperature of thermocouple wire (Chromel/Alumel). Then effort is being made to examine the rich mixtures, whose temperature will be lower than the melting point of Chromel/Alumel thermocouple. On this basis, it is decided to probe the temperature profile across a well stabilized flame for equivalence ratio of 1.7.

During the measurement, it is learnt that a careful attention is needed to rather handle the thermocouple, when it is inside the flame. Thermocouple may break even subjected to a little vibration because of thermal stress.

The temperature profile of premixed LPG-air Bunsen flame measured by a Chromel/Alumel thermocouple at an equivalence ratio of 1.7 is shown in fig.2.16. The temperature is measured along the flame height at the center of the burner. The difference between the adiabatic and temperature measured by the Chromel/Alumel thermocouple is 221K as shown in fig.2.16.

In order to cross check the temperature measurement by Chromel/Alumel thermocouple, Pt/Pt-13%Rh thermocouple of wire diameter 0.05 mm (bead diameter-0.085 mm) is used. The temperature profile measured by both the thermocouple is

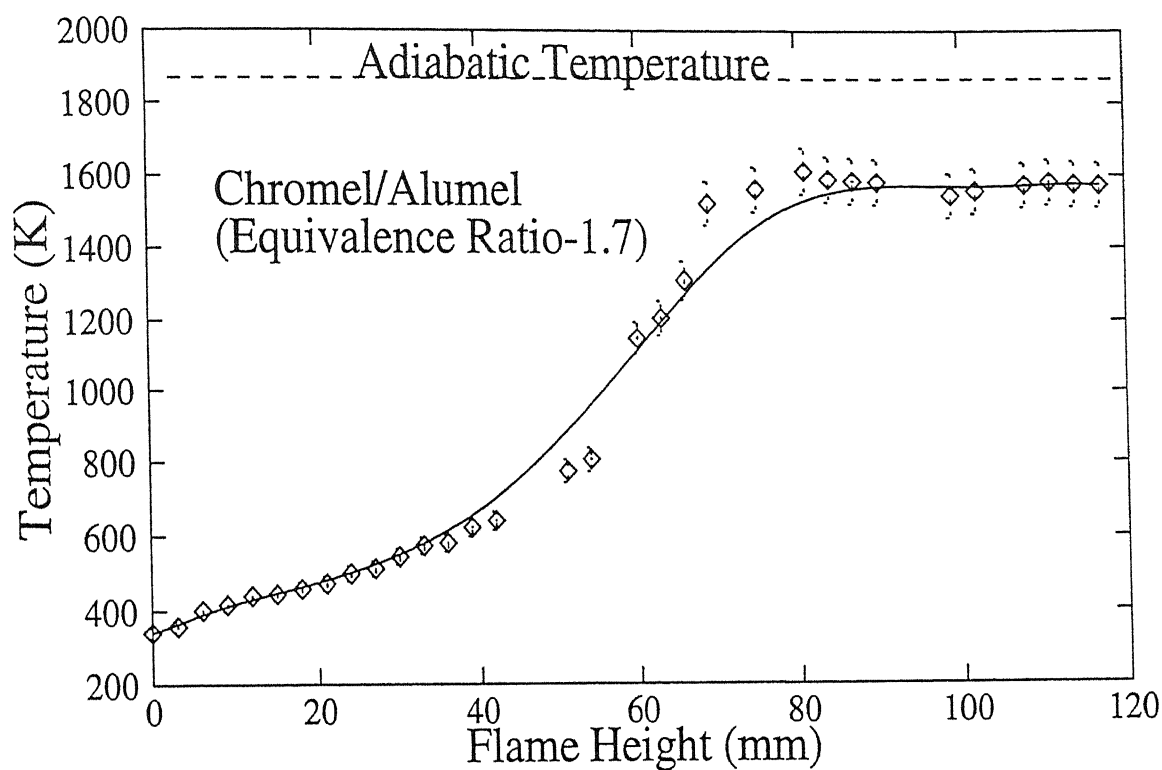


Figure 2.16: Temperature profile measured by Chromel/Alumel

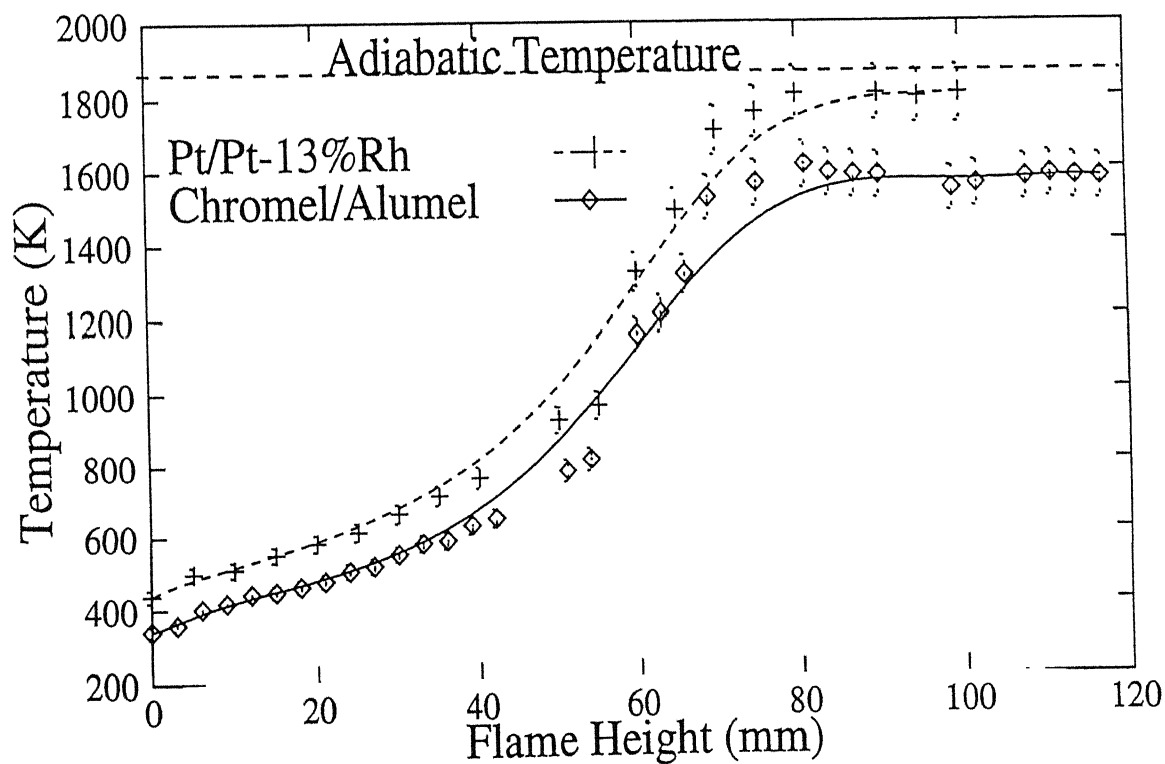


Figure 2.17: Comparison of temperature profile by different thermocouples

plotted in a single plot as shown in fig.2.17. It can be observed from the fig.2.17 that the peak temperature measured by Pt/Pt-13%Rh shows the difference of only 25 K from the adiabatic flame temperature. Therefore, it is concluded that the use of Pt/Pt-13%Rh thermocouple in the measurement of flame temperature will give a better result than Chromel/Alumel.

2.6 UNCERTAINTY ANALYSIS

The aim of any experiment is to measure some physical quantities as accurately as possible. Experimental error in the measurement must be estimated to arrive at the conclusion about the correctness of the result obtained. The error involves uncertainties of various kinds. The possible imperfection of the theory on which the experiment is based, the imperfection of the instrument and the observer are some of the major causes of uncertainties. Hence, it is essential to estimate the inaccuracies associated with the measured values to assess the validity of the results. The general procedure for estimating the uncertainties in the calculated quantities using measured data as described below [29] :

Let $x_1, x_2, x_3, \dots, x_i, \dots$ be the independent parameters (variables) in the experimental measurement, and $u_1, u_2, u_3, \dots, u_i, \dots$ be their relative uncertainties. Let R be the experimental result calculated from the measured data.

The quantity R can be expressed as

$$R = R(x_1, x_2, x_3, \dots, x_i, \dots, x_n)$$

The effect of error in measuring individual x_i on R may be estimated by analogy to derivative of a function.

A variation δx_i in x_i would cause R to vary according to,

$$\delta R_i = \frac{\partial R}{\partial x_i} \delta x_i$$

For applications, it is convenient to normalize the above equation by dividing throughout by R to obtain

$$\frac{\delta R_i}{R} = \frac{1}{R} \frac{\partial R}{\partial x_i} \delta x_i = \frac{x_i}{R} \frac{\partial R}{\partial x_i} \frac{\delta x_i}{x_i} \quad (2.27)$$

Equation (2.27) might be used to estimate the uncertainty intervals in the result R , due to variation in x_i . Substituting the uncertainty interval for x_i , namely

$$u_{R_i} = \frac{x_i}{R} \frac{\partial R}{\partial x_i} u_{x_i}$$

It can be shown that the best representation for the uncertainty interval of the result is

$$u_R = \pm \left[\left(\frac{x_1}{R} \frac{\partial R}{\partial x_1} u_{x_1} \right)^2 + \left(\frac{x_2}{R} \frac{\partial R}{\partial x_2} u_{x_2} \right)^2 + \dots + \left(\frac{x_n}{R} \frac{\partial R}{\partial x_n} u_{x_n} \right)^2 \right]^{1/2} \quad (2.28)$$

In our case, Q_A , Q_F and H be the three variables for determining burning velocity.

At stoichiometric composition ($\Phi = 1$)

Q_A (air flow rate) = 26.2 lit/min

Q_F (fuel flow rate) = $0.25 \times x + 0.16$ (x is the manometric deflection in cm)

$x = 30$ mm

$Q_F = 0.91$ lit/min

H (flame height) = 32 mm

it is estimated that the maximum possible error in the measurement of air flow rate would be 0.4 lit/min, 1.0 mm in manometric deflection and 1 mm in flame

height measurement.

$$S \text{ (flame surface area)} = \pi R \sqrt{R^2 + H^2} = 939.88 \text{ mm}^2$$

$$V \text{ (burning velocity)} = (Q_A + Q_F) / \pi R \sqrt{R^2 + H^2} = 48.09 \text{ cm/sec} = 28.85 \text{ m/min}$$

$$u_A = \pm (\text{expected error in } Q_A) / (\text{measured } Q_A) = \pm 0.4 / 26.2 = \pm 1.5\%$$

$$u_F = \pm (\text{expected error in } Q_F \text{ due to } x) / (\text{measured } Q_F) = \pm (0.25 \times 0.1) / 0.91 = \pm 2.75\%$$

$$u_H = \pm (\text{expected error in } H) / (\text{measured } H) = \pm 1.0 / 32.0 = \pm 3.13\%$$

$$\frac{\partial V}{\partial Q_A} = \frac{\partial V}{\partial Q_F} = \frac{1}{\pi R \sqrt{R^2 + H^2}} = 1063.96$$

$$\frac{\partial V}{\partial H} = \frac{-(Q_A + Q_F)H}{\pi R(R^2 + H^2)^{3/2}} = -835.92$$

The uncertainty in V can be obtained with the help of equation (2.27)

$$u_V = \pm \left[\left(\frac{Q_A}{V} \frac{\partial V}{\partial Q_A} u_A \right)^2 + \left(\frac{Q_F}{V} \frac{\partial V}{\partial Q_F} u_F \right)^2 + \left(\frac{H}{V} \frac{\partial V}{\partial H} u_H \right)^2 \right]^{1/2} = \pm 3.25\%$$

2.7 CONCLUSION

An extensive experimental study has been conducted to study the structure of laminar premixed LPG-air flames over a wide range of fuel-air ratios. Burning velocity of Bunsen flames is determined by area method. It is observed that the burning velocity of LPG-air premixed flames increases with increase in equivalence ratio and reaches a maximum value at slightly rich stoichiometric composition. With further increase in fuel concentration, burning velocity decreases. The maximum burning velocity of LPG-air flames is found to be 50.4 ± 3.5 cm/sec, at an equivalence ratio of 1.1.

A theoretical analysis has also been carried out to estimate the burning veloc-

ity. It is found out that the burning velocities calculated by theoretical analysis also follow the same trend as that of experimental values, but gives higher burning velocity in comparison to the measured. This is due to the fact that the adiabatic temperature is used while calculating the burning velocities.

Temperature profile of laminar premixed LPG-air flame has been determined by using Chromel/Alumel and Platinum/Platinum-13%Rhodium thermocouples for equivalence ratio of 1.7. The peak temperature of the flame obtained by both the thermocouple is lower than the adiabatic. However, temperature measured by Platinum/Platinum-13%Rhodium thermocouple is quite close to the adiabatic flame temperature.

Chapter 3

FLAME STABILITY

3.1 INTRODUCTION

A premixed flame can be stabilized between two limiting values of the gas flow rate. When the gas flow rate exceeds a certain maximum value, flame gets detached from the rim of the burner. This phenomena is called the lift-off of the flame. If the gas flow rate is increased further, a threshold value is reached at which the flame may go away from the domain of interest. This maximum value of the gas flow rate is known as blow-off limit. When the flow rate of the gas falls below a certain minimum threshold value, flame is not capable to anchor itself to the burner rim and moves into the burner. This minimum threshold value of the gas flow rate is known as flash-back limit.

3.2 LITERATURE SURVEY

A large number of papers have been reported regarding the stability of premixed hydrocarbon flames in the open literature. The first reported literature on the stability of hydrocarbon flames is the work of Harris et al. [3], who conducted experimental

studies on methane-oxygen premixed flames at normal temperature and pressure. In this paper, they have presented the results of velocity gradients, where flash-back or blow-off occurs. Simultaneously, Wohl et al. [30], studied the stability of laminar butane-air flames, covering a wide range of fuel-air ratios, starting from lean to rich mixtures. In this work, they have observed the flash-back and blow-off phenomena. Subsequently, Miller and Sitzler [31] gave stability results of n-butane-nitrogen dioxide flames. They put forward a procedure to adjust the mixture ratio and total gas flow rate for investigating the flash-back and blow-off limit as a function of burner diameter. In later studies, Bonillah [32] offered a general correlation between the velocity gradient of flow and flash-back or blow-off limits. They also gave some experimental results of stability limits by using butane-air and methane-air mixtures. The stabilization of propane-air flames in refractory tubes without a flame holder was investigated by Chen and Churchill [33] by determining the flash-back or blow-off limit.

3.3 EXPERIMENTAL PROCEDURE

The experimental set up used to study the stability of LPG-air flames is same as that described for the study of flame structure, as shown in fig.2.5. In order to investigate the stability of laminar premixed LPG-air flames, initially the flame is stabilized by adjusting the fuel-air ratio and total gas flow rate. Then, blow-off is determined by increasing the total gas flow rate (at constant LPG concentration) in small increments until the flame lifts-off from the burner port and finally blow-off occurs. Conversely, flash-back can be obtained by decreasing the total gas flow rate until flame starts to propagate inside the burner. This phenomena of flash-back and blow-off have been obtained by visual inspection.

3.4 RESULTS AND DISCUSSION

In the present work, experiments are conducted to determine the flash-back and blow-off limits of laminar premixed LPG-air flames covering a wide range of fuel-air ratios. The phenomena of flash-back is observed by decreasing the gas flow rate up to a minimum threshold value at which a flame is not capable to anchor itself on the burner port and rather moves into the burner. The results of flash-back for 12 mm diameter burner over a wide range of fuel-air ratios are presented in fig.3.1. It is evident from the figure that the region left to the curve is the flash-back zone. In this zone, the gas flow rate is less than the threshold value as marked in fig.3.1. In other words, if the flow rate decreases below this threshold value, the flame will move into the burner, this phenomena is called flash-back as defined previously. It is observed that the flash-back limit varies with fuel concentration. It can be noticed from the figure that the region, where the concentration of LPG is less than the stoichiometric composition, flash-back limit increases with increase in fuel concentration. The stoichiometric composition of LPG-air is shown by a dotted line. Above this dotted line, flash-back limit attains a maximum value at slightly rich stoichiometric composition and then decreases with further increase in fuel concentration, as shown in fig.3.1. The trend of the present results can be justified since the burning velocity of LPG-air flames attains a maximum value at slightly rich stoichiometric composition, as described in section 2.5.

Subsequently, similar experiments are also conducted for other burners of 15 and 18 mm diameter. The results of flash-back limit for all the burners are plotted in a single plot as shown in fig.3.2. It can be observed that the flash-back limit increases with increase in burner diameter keeping similar trend as that of 12 mm diameter burner.

The phenomena of flash-back can be explained by considering the boundary

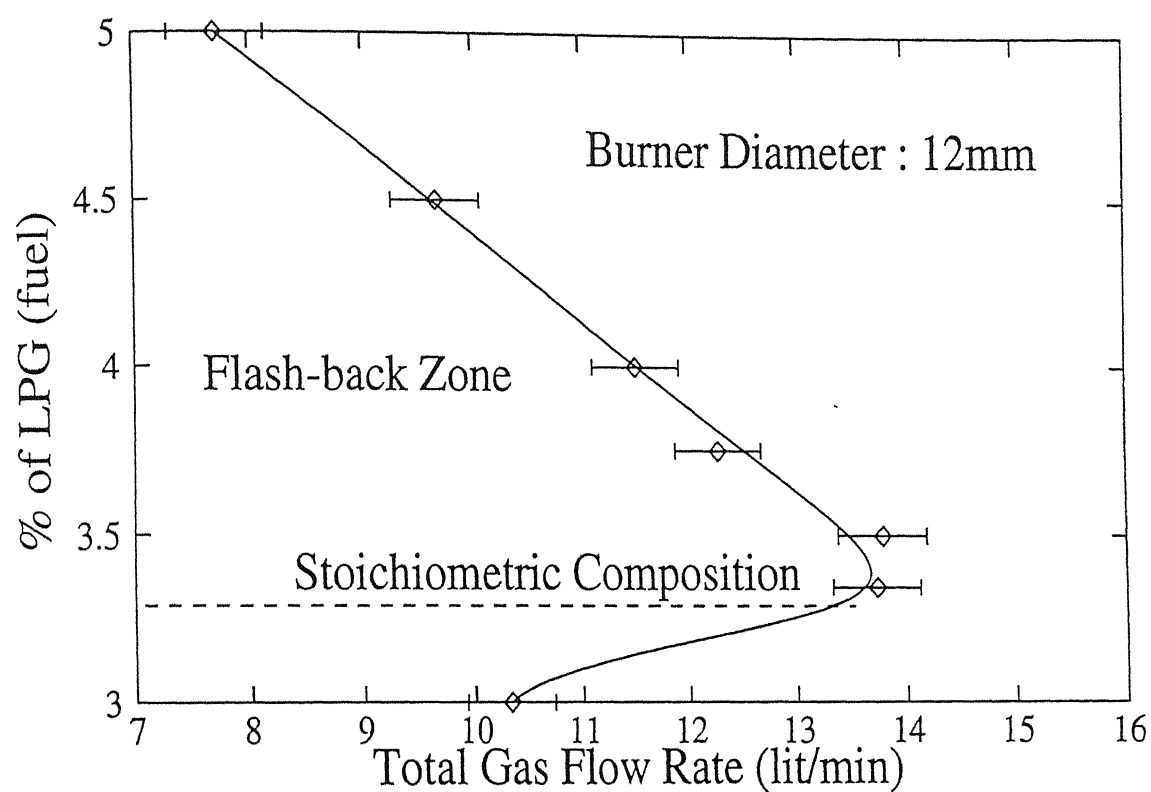


Figure 3.1: Flash-back limit of cylindrical burner : LPG-air

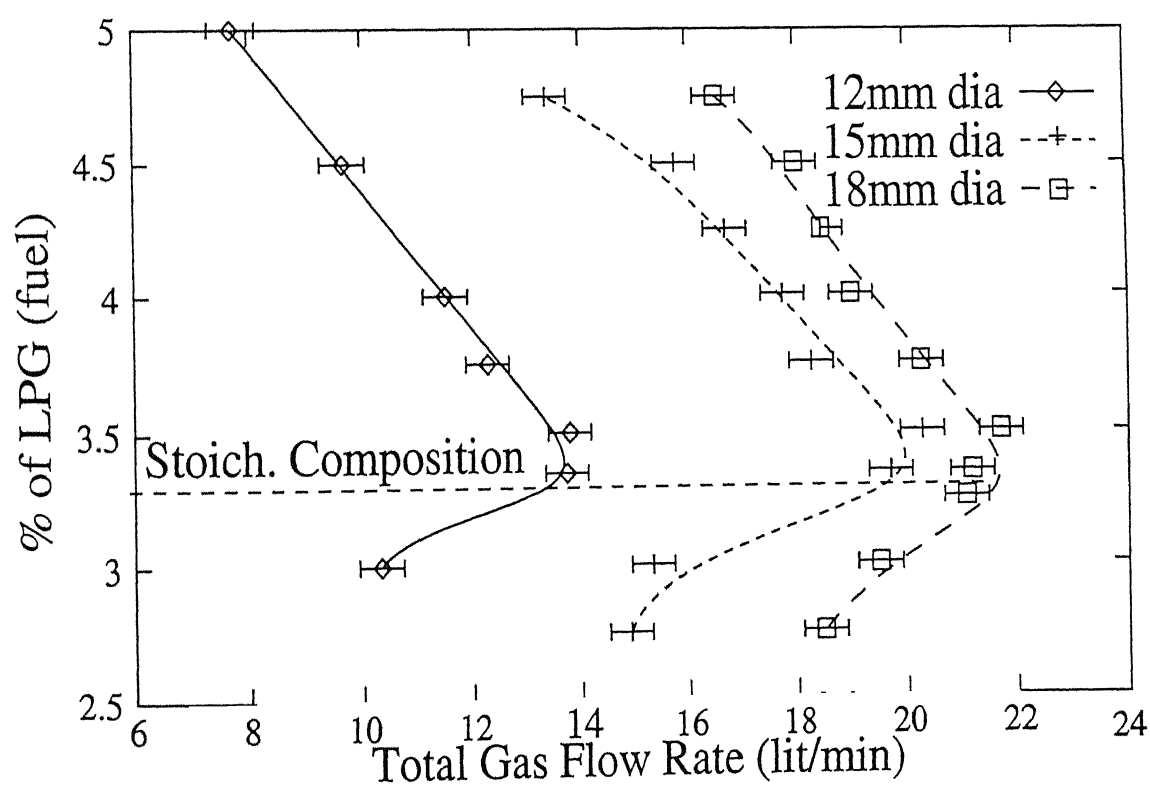


Figure 3.2: Flash-back limit for different cylindrical burners

velocity gradient around the burner rim. When the boundary velocity gradient falls below a minimum threshold value, at this condition, the normal component of the gas velocity to the flame surface also reduces and goes below the burning velocity in the entire cross sectional area of the burner. This threshold value is called the flash-back boundary velocity gradient. The boundary velocity gradient at flash-back condition can be expressed as given by Lewis and Von Elbe [34] :

$$g_f = 8V_f/D \quad (3.1)$$

where,

g_f = Velocity gradient at the tube wall below which flash back can occur

V_f = Flash-back velocity

D = burner diameter

It can be observed from the above equation that flash-back velocity is proportional to the burner diameter. That is the reason, why an increase in flash-back limit is observed with increase in burner diameter.

Experiments are also conducted to study the blow-off limits. Blow-off is determined by increasing the gas flow rate up to a maximum threshold value, at which a flame moves away from the burner port. Experimental results of blow-off limit for 12 mm diameter burner is shown in fig.3.3. It can be observed that the region right to the curve is the blow-off zone. In other words, if the total gas flow rate goes above the threshold value, the flame will go away from the domain of interest, this phenomena is called blow-off as defined previously. It can be noticed from the figure that blow-off increases with increase in fuel concentration. This observation can be explained in the following manner.

A flame gets lifted prior to the blow-off. At the lifting condition, the mixture composition becomes leaner caused due to dilution by the surrounding air and burn-

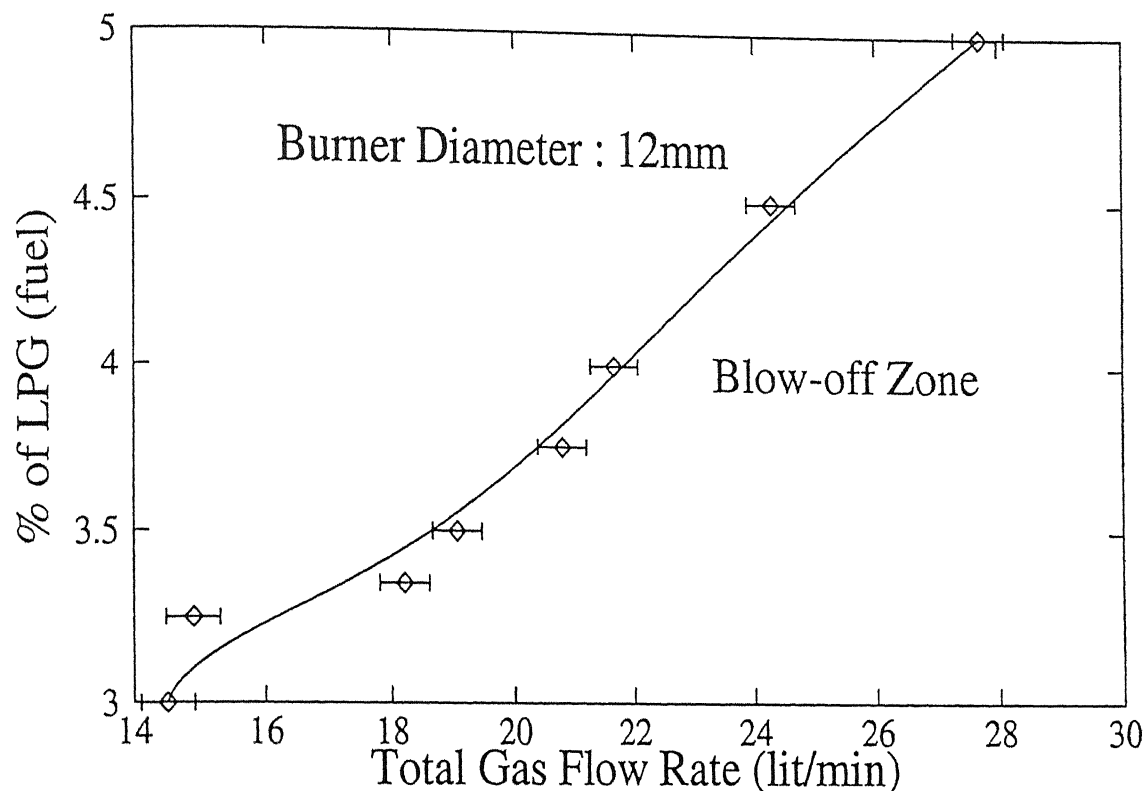


Figure 3.3: Blow-off limit of cylindrical burner : LPG-air

ing velocity decreases correspondingly. With increase in fuel concentration, mixture ratio moves towards stoichiometric composition. It is known that burning velocity attains maximum value at slightly rich stoichiometric composition, as described in section 2.5. Therefore, an increase in blow-off limit with fuel concentration is justified.

Similar experiments for blow-off are also conducted for other burners of 15 and 18 mm diameter. The results of blow-off limit for all the burners are plotted, as shown in fig.3.4. It can be noticed that the blow-off limit increases with increase in burner diameter keeping similar trend that of 12 mm diameter burner. This can be explained by considering the blow-off boundary velocity gradient similar to flash-back limit, given as :

$$g_b = 8V_b/D \quad (3.2)$$

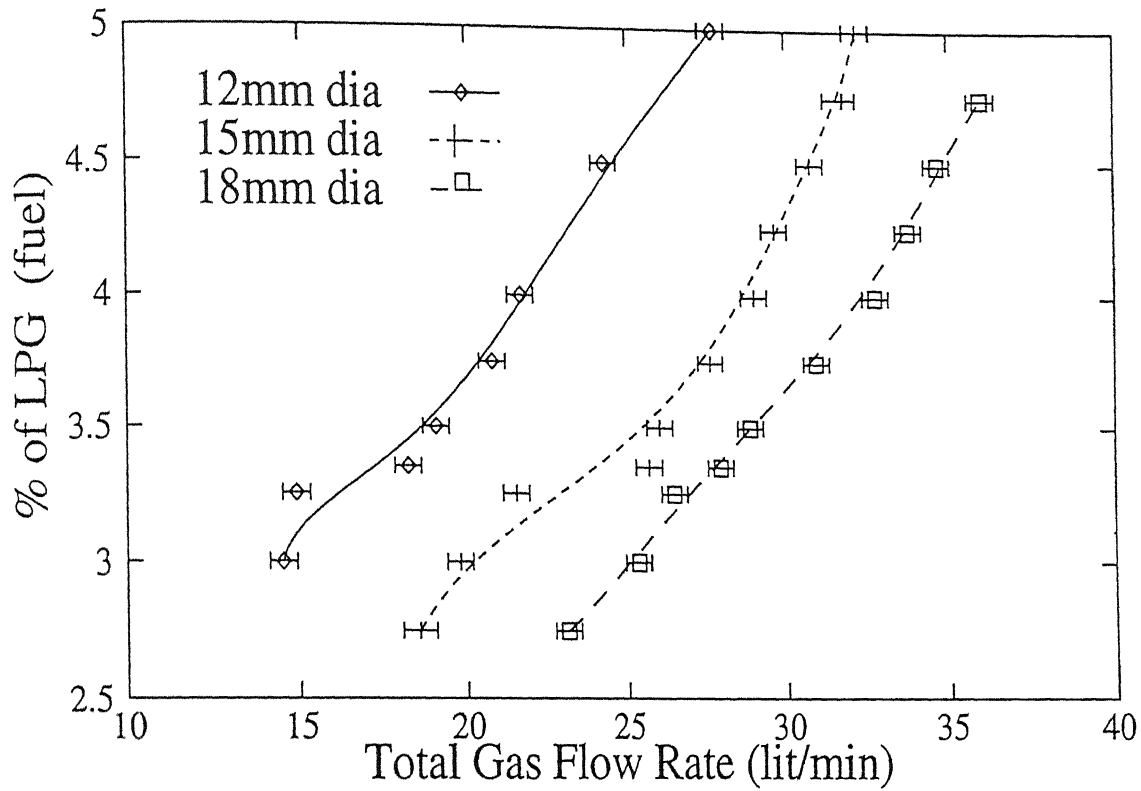


Figure 3.4: Blow-off limit for different cylindrical burners

Where,

g_b = velocity gradient at the tube wall after which blow off can occur

V_b = blow off velocity,

D = burner diameter

Now the results of boundary velocity gradients for flash-back and blow-off are presented in a single plot for 12 mm diameter as shown in fig.3.5. In this figure, the stable region of the flames are clearly indicated. Similar plots are also shown for other burners in fig.3.6 & 3.7. respectively. It can be observed that the stability range decreases with increase in burner diameter. Therefore, the operating conditions of the combustion must be kept between their stability limit for smooth operation of combustion devices.

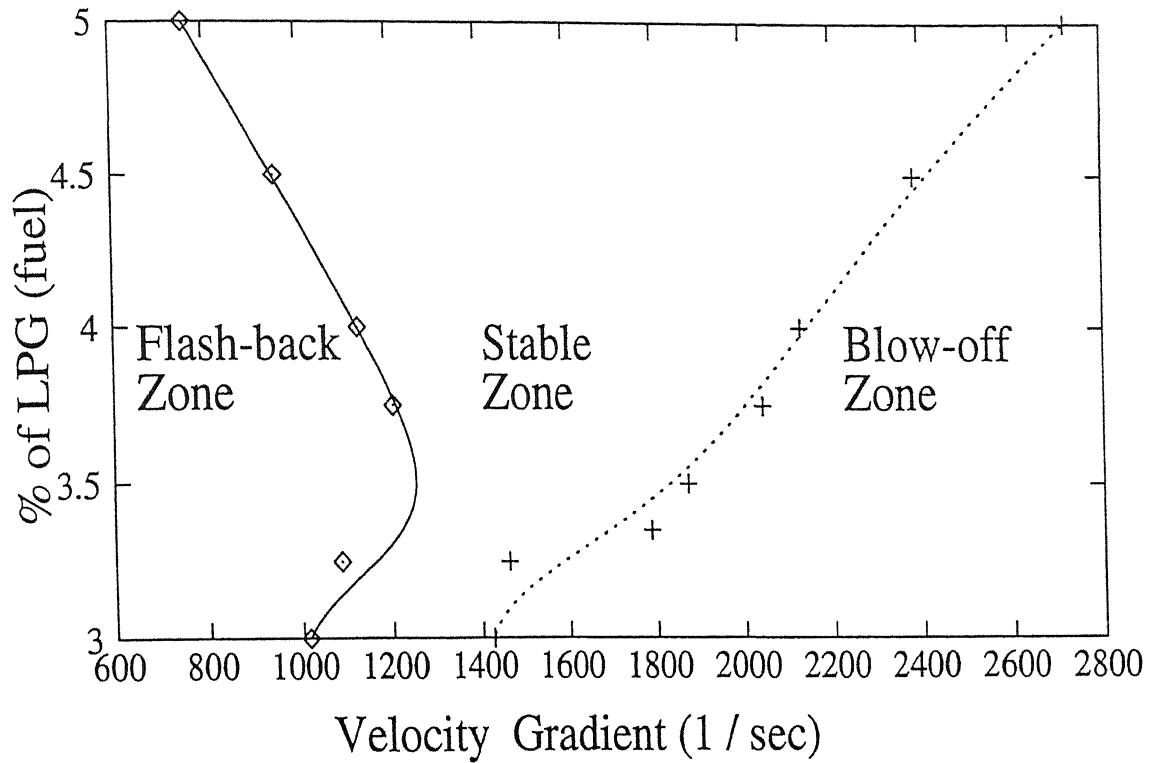


Figure 3.5: Region of stable LPG-air flames for 12mm dia burner

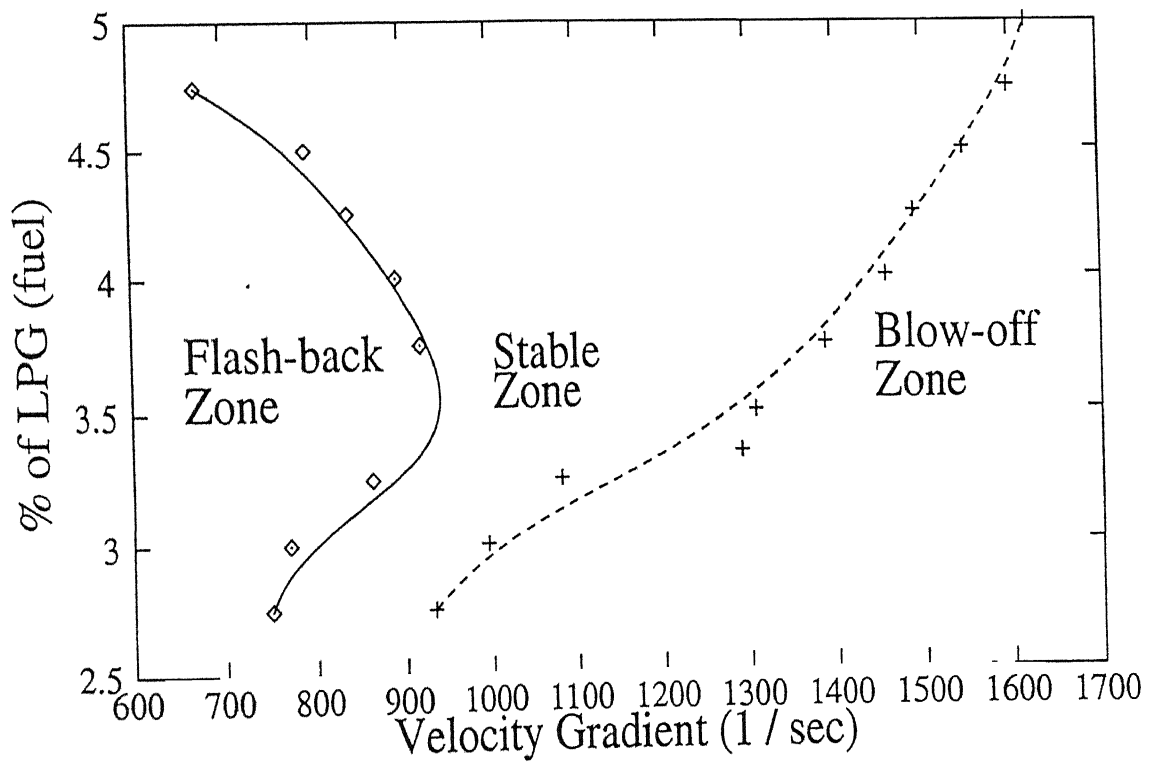


Figure 3.6: Region of stable LPG-air flames for 15mm dia burner

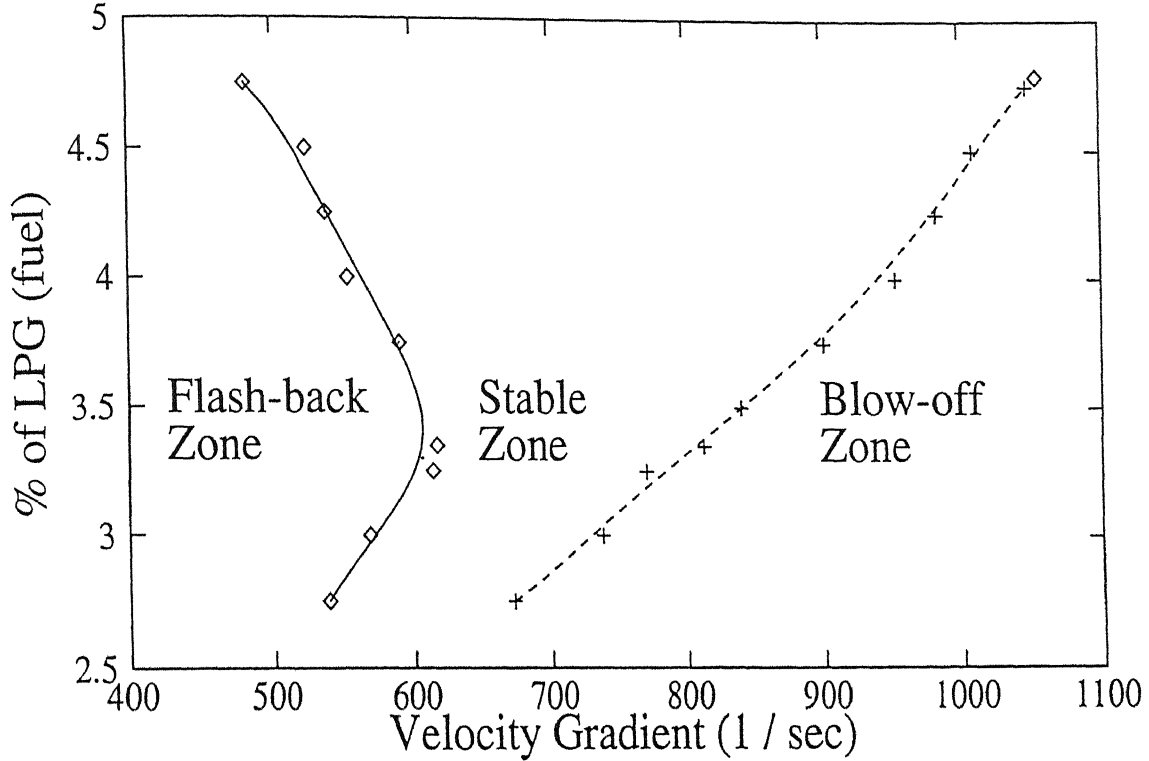


Figure 3.7: Region of stable LPG-air flames for 18mm dia burner

3.5 UNCERTAINTY ANALYSIS

Q_A and Q_F be the two parameters for determining the stability limit.

At 3.5% LPG concentration (flash-back limit)

$$Q_A \text{ (air flow rate)} = 13.3 \text{ lit/min}$$

$$Q_F \text{ (fuel flow rate)} = 0.25x + 0.16 \text{ (x is the manometric height in cm)}$$

$$x = 13 \text{ mm}$$

$$Q_F = 0.485 \text{ lit/min}$$

It is estimated that possible error in the measurement of air flow rate would be 0.4 lit/min and 1.0 mm in manometric deflection.

$$Q \text{ (Total gas flow rate)} = Q_A + Q_F = 13.3 + 0.485 = 13.785 \text{ lit/min}$$

$$u_A = \pm (\text{expected error in } Q_A) / (\text{measured } Q_A) = 0.4 / 13.3 = \pm 3.01 \%$$

$$u_F = \pm (\text{expected error in } Q_F \text{ due to } x) / (\text{measured } Q_F) = 0.25 \times 0.1 / 0.485 = \pm 5.15 \%$$

$$\frac{\partial Q}{\partial Q_A} = \frac{\partial Q}{\partial Q_F} = 1$$

The uncertainty in Q can be obtained with the help of equation (2.28)

$$u_Q = \pm \left[\left(\frac{Q_A}{Q} \frac{\partial Q}{\partial Q_A} u_A \right)^2 + \left(\frac{Q_F}{Q} \frac{\partial Q}{\partial Q_F} u_F \right)^2 \right]^{1/2} = \pm 2.91\%$$

3.6 CONCLUSION

Extensive experimental studies have been conducted on the stability of LPG-air flames. The laminar premixed LPG-air flames have been stabilized between the flash-back and blow-off limits. It is found out that the maximum flash-back occurs at slightly rich stoichiometric composition. The flash-back limit increases with fuel concentration for fuel lean mixtures. On the other hand, the flash-back limit decreases with further increase in fuel concentration for fuel rich mixtures. But, it is observed that blow-off limit increases with fuel concentration over the whole range of fuel-air mixture ratios.

The flash-back and blow-off limits have been explained in terms of boundary velocity gradient of the flow at flash-back or blow-off conditions. It has been found from the present investigation that the velocity gradient depends upon the volumetric flow rate of gases. Results of boundary velocity gradient for flash-back and blow-off are presented in a single plot in which stability region of flames can be clearly recognized. It has also been observed that the range of stability decreases with increase in burner diameter. The stability plot can be very useful for designing the combustion devices using LPG-air mixtures.

Chapter 4

FLAMMABILITY LIMITS

4.1 INTRODUCTION

The first study of flammability limits dates back to 1816, when Humphry Davy was working on his famous safety lamp for the coal mine workers. Flammability limits can be defined as the range of fuel-oxidizer mixture ratio between which a flame can propagate. However, sufficient energy must be provided to initiate the flame which insists the flame to propagate over a fresh reaction mixture. The lower fuel lean mixture up to which the flame can propagate is termed as Lower Flammability Limit (LFL), while upper fuel rich mixture is known as Upper Flammability Limit (UFL). The information of these limits are very important for burning a mixture and also for fire safety point of view. If a fuel-oxidizer mixture needs to be burnt, it must lie within the limits of flammability. The limits are quoted either as percentage of fuel in the mixture or in terms of equivalence ratio.

4.2 LITERATURE SURVEY

A lot of experimental work has been done on the measurement of flammability limits of fuel-oxidizer mixtures. The oxidizer used is generally air or oxygen, and the fuels are hydrogen or hydrocarbon. Among the hydrocarbons, methane has been extensively studied due to its presence in natural gas, town gas, etc.

In some of the early experiments, Burgess & Wheelers [35] used cylindrical tubes of 6 cm diameter and 200 cm long. It was found out that the flammability limit differed depending on the point of ignition- top, bottom or central with respect to the tube. Subsequently, White [36] consolidated the then existing data on flammability limits. He also attempted to systematically obtain the flammability limits of a number of fuel-air mixtures based on various criteria like upward, downward and horizontal propagation and also based on the tube sizes of 2.5, 5 & 7.5 cm diameter. It was also observed by White [36] that the flammability limits are not reliable when the tubes of diameter less than 2.5 cm are used since the heat loss begin to dominate. The significant conclusion from his experiments was that the wall cooling effect has a little influence on the lean limits using larger diameter tube (7.5 cm).

Pressure rise in the burned gas due to heating, producing a compression of unburned gas has not been considered by both Burgess & Wheelers [35] and White [36]. In their experiments, the burned gas is kept closed and the limit data reported are consistently higher (5.4% methane for upward propagation in 5cm tube). The later results reported by Egerton & Powling [37] using the tubes of the same size, but kept the burned end open are lower (5.26%) than the results obtained by Wheeler [35] & White [36]. The effects of radiative heat loss from the flame was also obtained by Egerton & Powling [37] and found that the flammability range of hydrocarbon-air mixture was much affected by radiative heat loss.

Subsequently, Coward & Jones [38] made flammability limits measurement by

using vertical glass tube of 5.1 cm diameter, 180 cm long and filled with the gas mixture, to be tested for flammability. Electric spark ignition was used at the bottom. The mixture was considered flammable, if a flame front travels upward through the entire length of the tube. The mixture is considered non-flammable, if the flame front is not initiated or after initiation, travels only few distances and extinguishes midway.

Although a large number of papers regarding the flammability limits of hydrocarbon-air flames are available. But to the best of our knowledge, no one has analyzed the flammability limits of LPG-air mixture, which is extensively being used in domestic as well as industrial combustion devices. Therefore, the present work is intended to study the flammability limits of LPG-air flames.

4.3 EXPERIMENTAL PROCEDURE

In order to investigate the flammability limits of laminar premixed LPG-air flames, an experimental rig has been designed and developed in our laboratory. A schematic of this experimental rig is shown in fig.4.1, which consists of flammability tubes, mixing chamber, fuel & air supply lines with controlling valves etc. Flammability tube is made by borosilicate glass of 5 cm I. D. and 1.2 m length. This is chosen according to the standard of U. S. Bureau of Mines [39].

A metered quantity of fuel and air of desired equivalence ratio are mixed in a mixing chamber. After mixing, LPG-air mixture are allowed to pass through the flammability tube at the bottom of which a heating filament is inserted for igniting fuel-air mixture. The heating element is made of nichrome wire of 0.5 mm diameter and 10 cm length. It is being heated by supplying electricity of 20 Volts through a variac. At the bottom of the flammability tube, a strainer is attached through which LPG-air mixture is being passed. A number of steel balls are placed

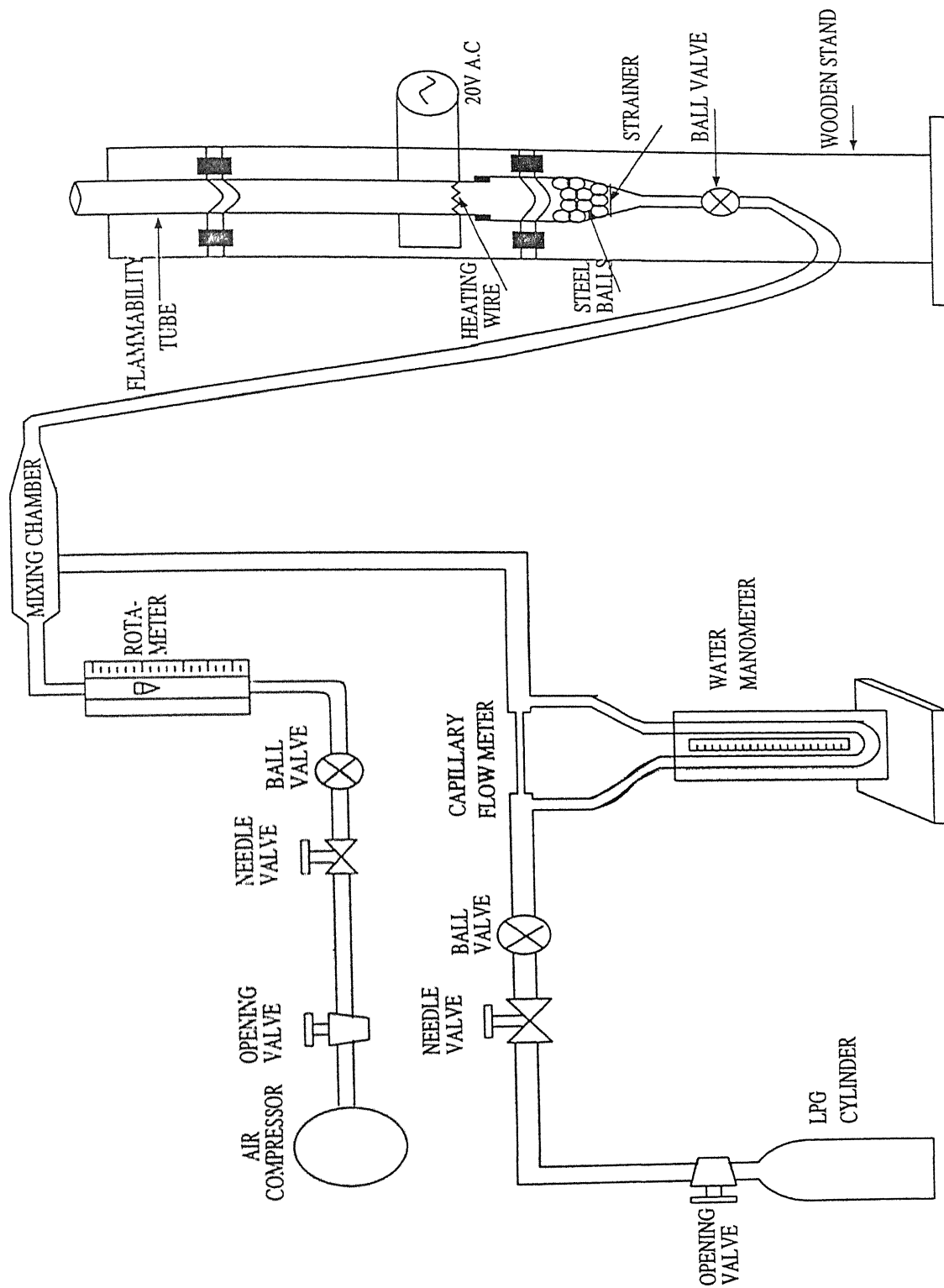


Figure 4.1: Schematic of test rig used to measure flammability limits : LPG-air

above the strainer as shown in fig.4.1, for laminarising the flow. This also acts as flame interceptor in case the flame enters into it. Once the mixture gets ignited, the resulting flame is moved in upward direction. When flame propagates over the entire length of the tube, the mixture is said to be flammable according to the standard of U.S. Bureau of Mines [39]. The flammability limits are determined by visual inspection of flame propagation.

An arrangement is also made to study the flammability limits for downward propagation of flames by allowing the flame to propagate downward as shown in fig.4.2.

The effect of dilution on the flammability limits is investigated by diluting the LPG-air mixture with nitrogen gas in a mixing chamber. Nitrogen is supplied from a commercially available nitrogen cylinder. A calibrated rotameter is used to measure the nitrogen flow rates. LPG and nitrogen are mixed through a 'T' shape connector as shown in fig.4.3 and subsequently passes to a mixing chamber, where air is also being added to achieve the required mixture composition. The flammability limits for varying nitrogen concentration are measured by similar procedure, as described above.

4.4 RESULTS AND DISCUSSION

In the present work, experiments are conducted for investigating the flammability limits of laminar premixed LPG-air flames covering a wide range of fuel-air ratios by the procedure mentioned in section 4.3. A heating element made of nichrome wire, connected with a variac is used to ignite the mixture. With several attempts, it is found that the electricity supply of 20 V generates sufficient amount of energy to ignite the mixture.

It is observed that the lean flammability limit for upward propagation is at

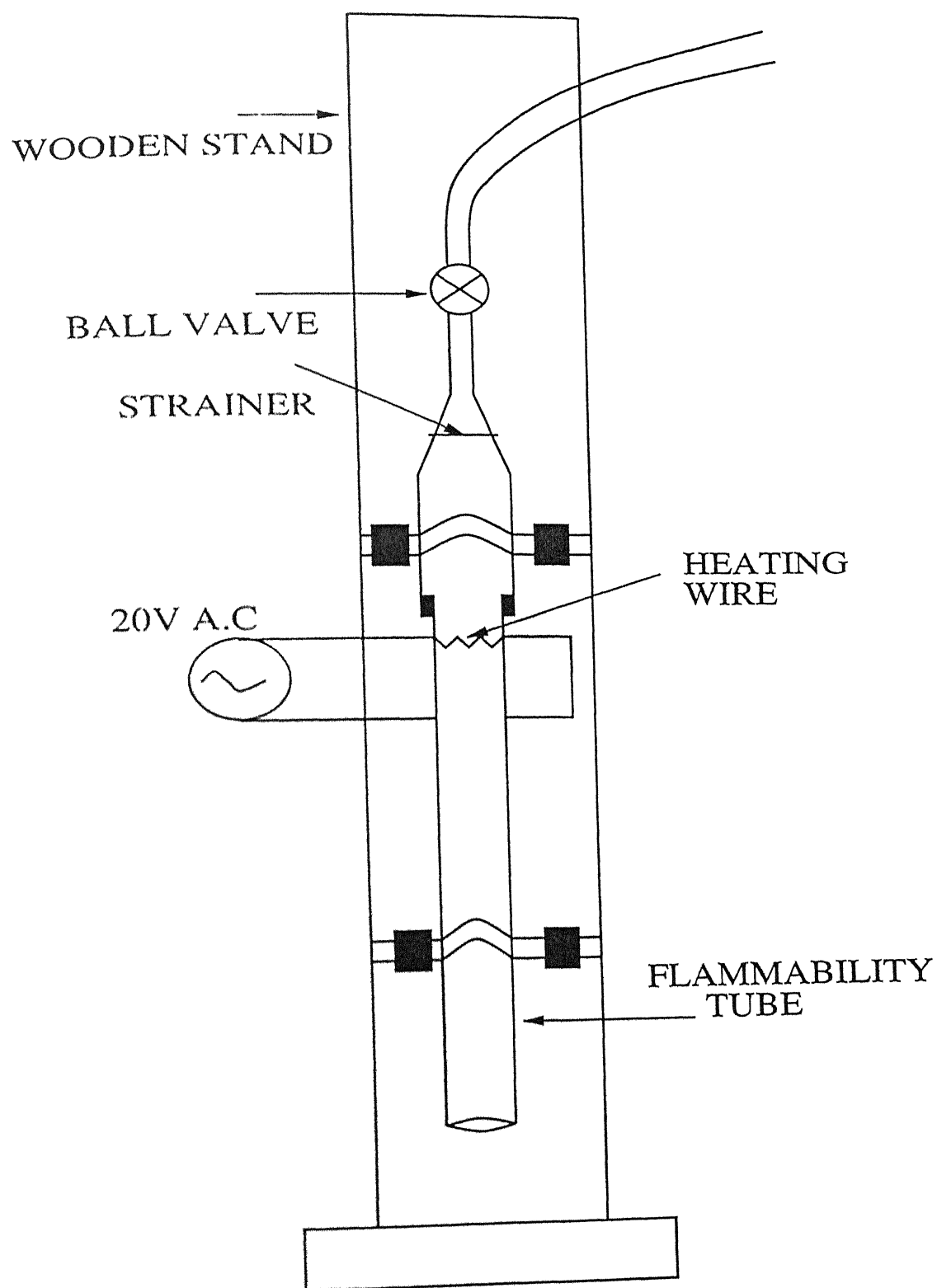


Figure 4.2: Schematic of test rig used to measure flammability limits for downward propagation of flames

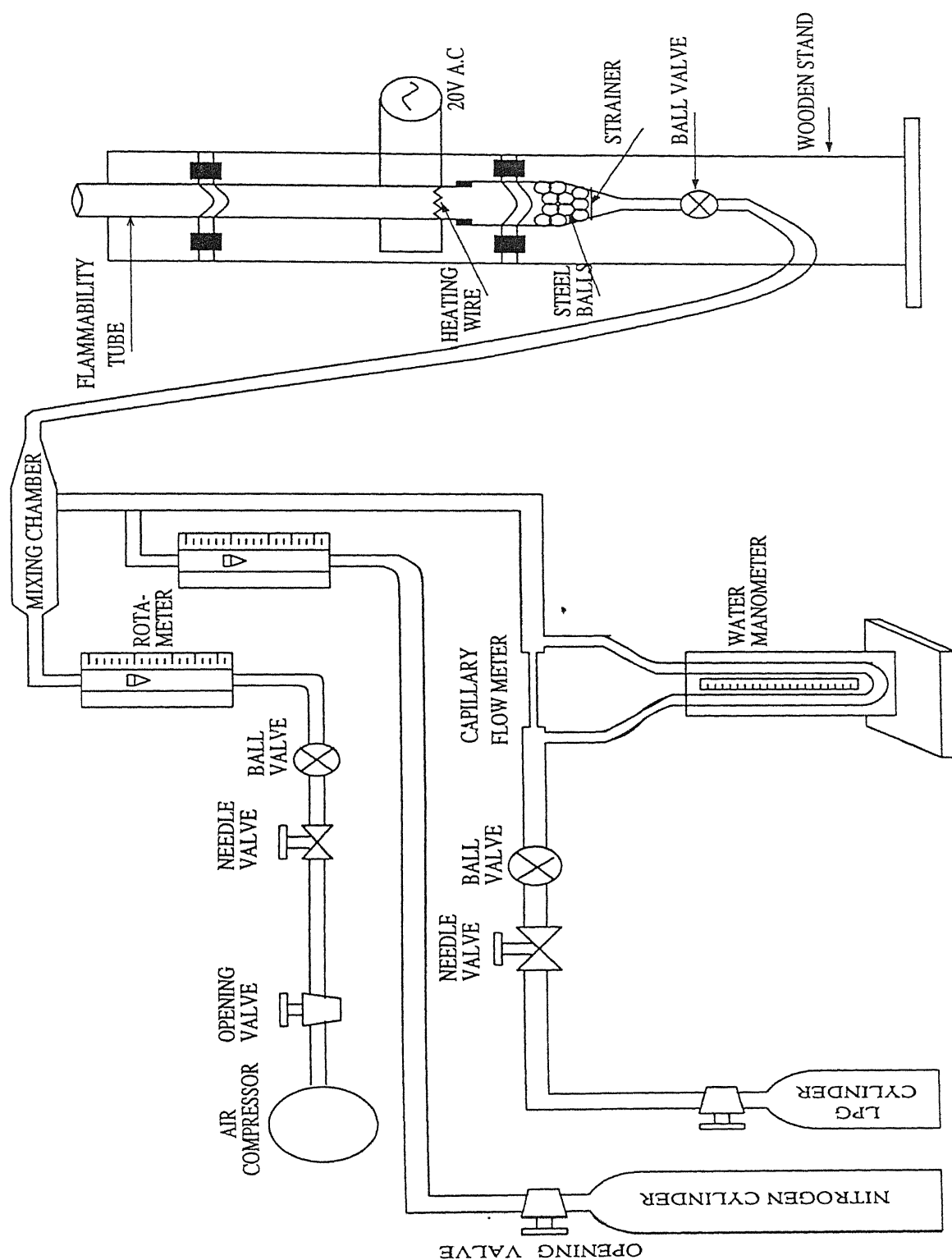


Figure 4.3: Schematic of test rig used to measure flammability limits :
LPG-air-nitrogen

Gas mixture	Upward limit (% of fuel)	Downward limit (% of fuel)
LPG-air (experimental data)	1.81 (lean) - 8.86 (rich)	1.87 (lean) - 7.69 (rich)
Propane-air	2.1 - 9.5	***
Butane-air	1.8 - 8.4	***

Table 4.1: Flammability limit data for hydrocarbon flames

an equivalence ratio of 0.53 or 1.81% of LPG (by volume). In contrast, the rich flammability limit is at an equivalence ratio of 2.8 or 8.86% of LPG. In order to validate our present results, a comparison is made with the available flammability data in literature for propane-air & butane-air mixture [40], given in table 4.1. It can be noticed from table 4.1 that the present result falls between the result of flammability limits for both butane-air & propane-air mixtures. Therefore, the present results of flammability limit for LPG-air mixture are within the expected value.

Experiments are also conducted to investigate the flammability limits of LPG-air mixture for downward propagation of flames. It is observed that the lean flammability limit is at an equivalence ratio of 0.55 or 1.87% of LPG (by volume), and rich flammability limit is at an equivalence ratio of 2.4 or 7.69%, as shown in table 4.1. It is noticed from the table that the flammability range for upward propagation is wider than the downward propagation. The reason can be explained in the following manner.

When a mixture gets ignited at the top of the tube, the flame will propagate downward only if the burning velocity is higher than that of convective rise of hot combustion product. In contrast, when mixture is ignited at the base of the tube, the flame moves upward and the convective rise of the hot gases increases the burning velocity. This is the reason, why flammability range for upward propagation is wider than the downward propagation.

In order to investigate the dilution effects on the flammability limits of LPG-

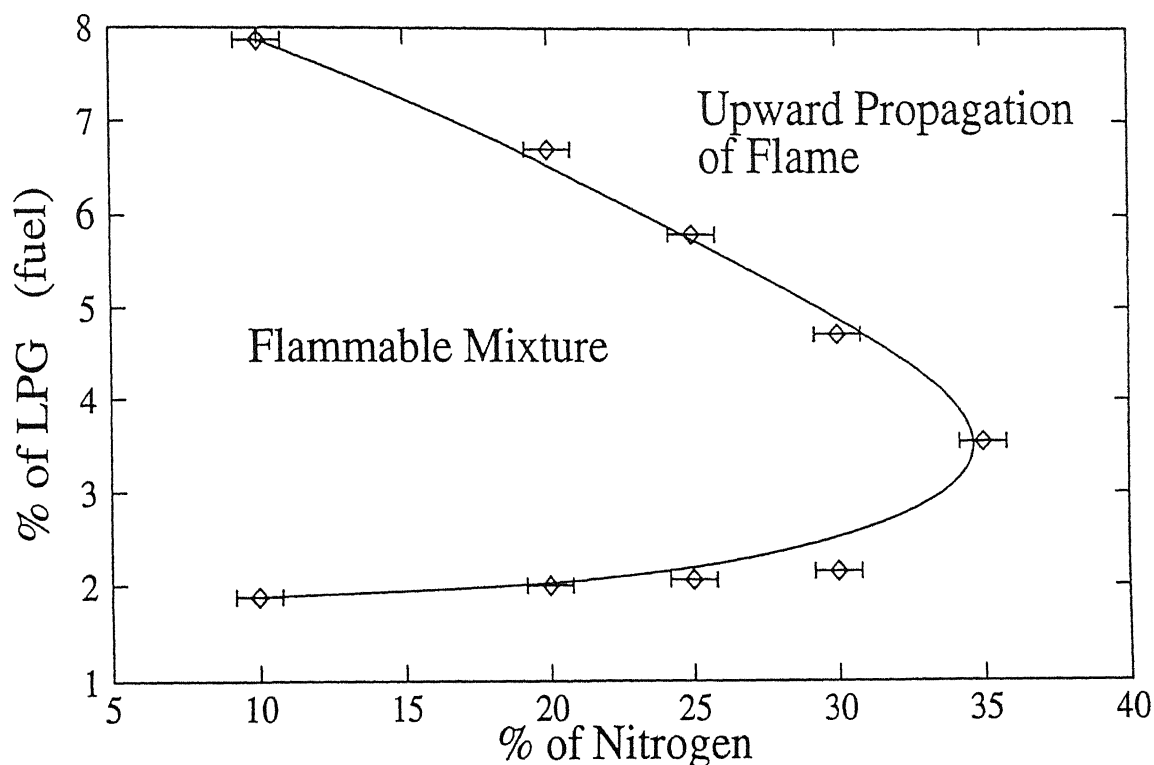


Figure 4.4: Flammability limits of LPG-air-nitrogen flames

air mixture, experiments are conducted by adding the nitrogen gas in the LPG-air mixture for both upward and downward propagation of flames. The result of flammability limits for upward flame propagation over a wide range of mixture composition is shown in fig.4.4. Subsequently, similar experiments are conducted for downward propagation of flames. The results of flammability limits for both upward and downward propagation are plotted in a single plot as shown in fig.4.5. It is observed that the flammability range of LPG-air mixture becomes narrow with addition of nitrogen gas. It is known that the addition of nitrogen gas decreases the flame temperature. Therefore, decrease in flammability range with the addition of nitrogen gas is justified.

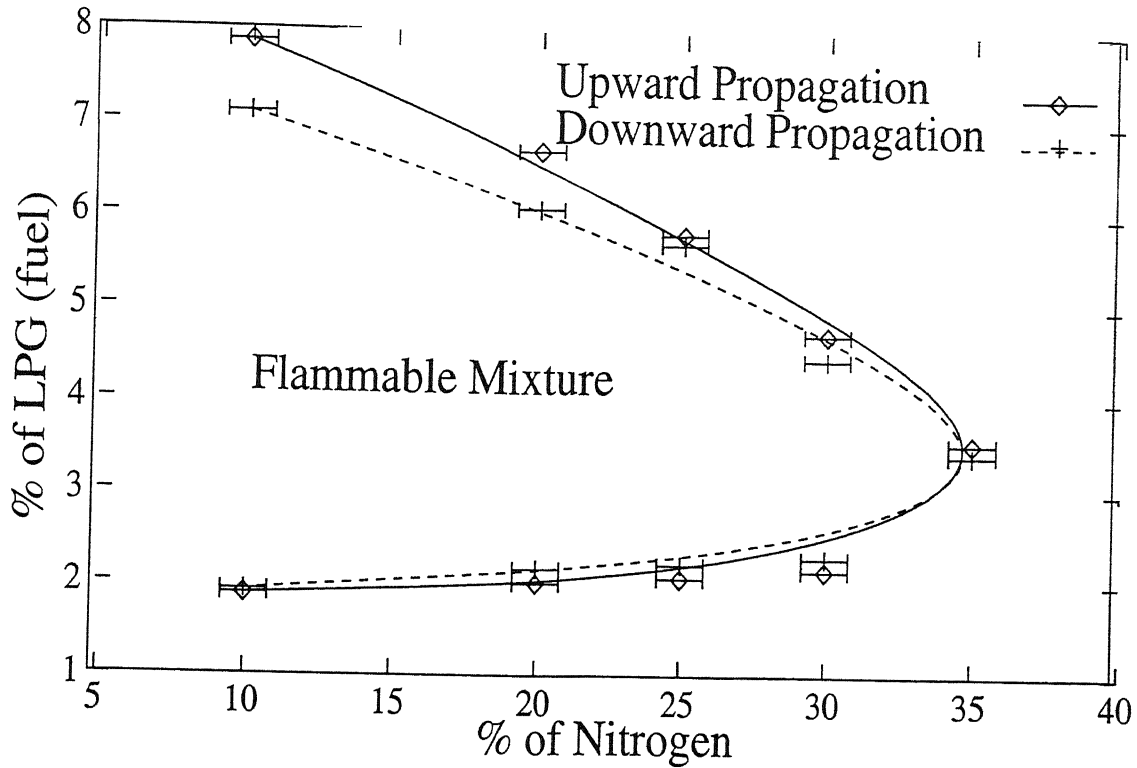


Figure 4.5: Comparison of upward & downward propagation of flames

4.5 UNCERTAINTY ANALYSIS

Q_A and Q_F be the two parameters for determining the flammability limits.

At rich limit, $\Phi = 2.8$ (for upward propagation)

Q_A (air flow rate)= 14.51 *lit/min*

Q_F (fuel flow rate)= $0.25x + 0.16$ (x is the manometric deflection in cm)

$x = 50$ mm

$Q_F = 1.41$ *lit/min*

It is estimated that possible error in the measurement of air flow rate would be 0.4 *lit/min* and 1.0 mm in manometric deflection.

Φ (equivalence ratio)= $(Q_F/Q_A)_{actual} / (Q_F / Q_A)_{stoichiometry} = 2.8$

$u_A = \pm(\text{expected error in } Q_A) / (\text{measured } Q_A) = 0.4 / 14.51 = 2.76 \%$

$u_F = \pm(\text{expected error in } Q_F \text{ due to } x) / (\text{measured } Q_F) = 0.25 \times 0.1 / 1.41 = 1.77\%$

$$\frac{\partial \Phi}{\partial Q_A} = -0.193$$

$$\frac{\partial \Phi}{\partial Q_F} = 1.986$$

The uncertainty in Φ can be obtained with the help of equation (2.28)

$$u_\Phi = \pm \left[\left(\frac{Q_A}{\Phi} \frac{\partial \Phi}{\partial Q_A} u_A \right)^2 + \left(\frac{Q_F}{\Phi} \frac{\partial \Phi}{\partial Q_F} u_F \right)^2 \right]^{1/2} = \pm 3.27\%$$

4.6 CONCLUSION

In this chapter, the experimental study of flammability limits of LPG-air mixture has been described. A fuel-air mixture can be flammable between two limiting values. It is found that the lower flammability limit (LFL) is 1.81% of LPG and upper flammability limit (UFL) is 8.86% of LPG for upward propagation. Whereas, for downward propagation, LFL is 1.87% and UFL is 7.69 % of LPG. It is concluded that the flammability limits for upward propagation is wider than the downward propagation.

The addition of Nitrogen gas to the flammability limits of LPG-air mixture has been studied in this work. It is found that the addition of nitrogen gas to the LPG-air mixture causes the limits to narrow and with sufficient amount of nitrogen gas, the LPG-air mixture are non-flammable. The flammability plot has been given which can be very useful for developing fire extinguisher and other combustion devices.

Chapter 5

SUMMARY

5.1 SUMMARY OF THE PRESENT WORK

In the present work, experimental studies have been conducted to study the laminar premixed LPG-air flames covering a wide range of fuel-air ratios. The investigation of premixed LPG-air flames have been carried out by dividing it into three sections, namely flame structure, flame stability and flammability limits. A premixed flame is characterized by its color, shape, burning velocity, temperature and concentration profile. Flame structure has been investigated by using a cylindrical tube Bunsen burner. It is found out that at very lean mixture, flame is conical and slightly rounded at the tip and appears blue. With increase in fuel concentration, rounding of the tip increases and color of the flame changes to green. At equivalence ratio of 1.5, flame surface does not remain continuous and tip opening can be observed.

Burning velocities which represent the flame structure to a larger extent are measured by area method. The maximum burning velocity of laminar premixed LPG-air flames is found to be 50.4 ± 3.5 cm/s at an equivalence ratio of 1.1. As no reliable data of burning velocity of premixed LPG-air flames are available in the literature, so, comparison of the present results are made with the burning velocity

of propane-air and butane-air flames and it is found out that the present results are within the expected trend of propane-air and butane-air flames. Burning velocities are also calculated by theoretical analysis, which is based on adiabatic flame temperature. A comparison of the present results is also made with the calculated values of burning velocity and concluded that both the values follow the same trend. However, the burning velocities calculated by theoretical analysis are having higher values than the experimentally measured values.

In order to determine the temperature profile, two different thermocouple namely Chromel/Alumel and Platinum/Platinum-13%Rhodium have been used. Temperature is measured at an equivalence ratio of 1.7. It is observed that the peak temperature measured by Pt/Pt-13%Rh is higher than the Chromel/Alumel thermocouple and close to the adiabatic flame temperature.

Extensive experimental studies have been conducted on the stability of LPG-air flames. It is observed that the LPG-air flames can be stabilized between two limiting values called flash-back and blow-off limit. For a 12 mm diameter burner, flash-back limit increases with the fuel concentration for fuel lean mixture, attains a maximum value at slightly rich stoichiometric composition and then decreases with further increase in fuel concentration. Similar trends are also observed for 15 & 18 mm diameter burner with increase in flash-back limit. But it is observed that the blow-off limit increases with increase in fuel concentration over the whole range of fuel-air ratios. With increase in burner diameter, blow-off limit increases keeping the similar trend for all the burners.

In order to investigate the flammability limits of premixed LPG-air flames, a standard flammability tube is used. Flammability limits are determined for both upward and downward propagation of flames. It is found out that the upward propagation is wider than the downward propagation. It is also found that the flamma-

bility limits of LPG-air mixture decreases with the addition of nitrogen gas keeping similar trends as reported by other investigators for hydrocarbon-air mixtures.

5.2 SCOPE FOR THE FUTURE WORK

Experiments should be conducted to measure the burning velocities by angle method, particle track method, constant volume method, etc. Due to limitation of apparatus, present work is concerned only with area method. For measuring the temperature profile, new intuitive type technique, like Laser Raman Spectroscopic technique should be used, which will give the more precise results in comparison to thermocouple.

In the present work, stability of premixed LPG-air flames have been characterized. However, there is a scope to explore the further extension in the stability limits, that will be more useful for designing a combustion device.

The effect of dilution on the flammability limits of LPG-air mixture has been investigated by adding nitrogen gas to the mixture. Hence, further work can be carried out by addition of other inert gases like helium, argon, carbon dioxide, etc. in the LPG-air mixture.

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